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Peer Design Review

Gamma-ray Large Area Space Telescope (GLAST)

Large Area Telescope (LAT)

Calorimeter (CAL) Subsystem Preliminary Design Report

CHANGE HISTORY LOG

Revision	Effective Date	Description of Changes	DCN #
1		Initial Release	

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1 PURPOSE

This document presents the status of the GLAST LAT Calorimeter subsystem design and planning in support of the July 27, 2001 Peer Design Review.

DEFINITIONS

2 ACRONYMS AND DEFINITIONS

ACD	The LAT Anti-Coincidence Detector Subsystem
AFEE	Analog Front End Electronics – CAL analog and readout boards
BTEM	Beam Test Engineering Model – CAL module built in development program
CAL	The LAT Calorimeter Subsystem
CDE	CsI Detector Element – CAL crystal with bonded PIN diodes and wrap
CES	Checkout Electronics System (Part of electrical ground support equipment
COTS	Commercial, off-the-shelf
FOV	Field of View
FWHM	Full Width Half Maximum
GLAST	Gamma-ray Large Area Space Telescope
GSE	Ground Support Equipment – test equipment and fixtures needed in assembly and test of the CAL modules
IOC	Instrument Operations Center
IRD	Interface Requirements Document
LAT	Large Area Telescope
MC	Monte Carlo
MSS	Mission System Specification
NRL	Naval Research Laboratory
PEM	Pre Electronics Module – CAL mechanical structure with CDEs installed
PI	Principal Investigator
SAS	Science Analysis Software
SRD	Science Requirements Document
SSC	Science Support Center
T&DF	Trigger and Data Flow Subsystem (LAT)
TBR	To Be Resolved
TKR	The LAT Tracker Subsystem

2.1 Definitions

γ	Gamma Ray
$\mu\text{sec}, \mu\text{s}$	Microsecond, 10^{-6} second
A_{eff}	Effective Area
Analysis	A quantitative evaluation of a complete system and /or subsystems by review/analysis of collected data.
Arcmin	An arcmin is a measure of arc length. One arcmin is 1/60 degree.
Arcsec	An arcsec is a measure of lengths of arc. One arcsec is 1/60 arcmin
Background Rejection	The ability of the instrument to distinguish gamma rays from charged particles.
Backsplash	Secondary particles and photons originating from very high-energy gamma-ray showers in the calorimeter giving unwanted ACD signals.
Beam Test	Test conducted with high energy particle beams
cm	centimeter
Cosmic Ray	Ionized atomic particles originating from space and ranging from a single proton up to an iron nucleus and beyond.
Dead Time	Time during which the instrument does not sense and/or record gamma ray events during normal operations.
Demonstration	To prove or show, usually without measurement of instrumentation, that the project/product complies with requirements by observation of results.
eV	Electron Volt
Field of View	Integral of effective area over solid angle divided by peak effective area.
Front Response	Response as measured in the thin layers of the Tracker
g	unit of gravitational acceleration, $g = 9.81 \text{ m/s}^2$
Geometric factor	is Field of View times Effective Area
GeV	Giga Electron Volts. 10^9 eV
Inspection	To examine visually or use simple physical measurement techniques to verify conformance to specified requirements.
MeV	Million Electron Volts, 10^6 eV
ph	photons
s, sec	seconds
Simulation	To examine through model analysis or modeling techniques to verify conformance to specified requirements
sr	steradian, A steradian is the solid (3D) angle formed when an area on the surface of a sphere is equal to the square of the radius of the sphere. There are 4 Pi steradians in a sphere.
Testing	A measurement to prove or show, usually with precision measurements or instrumentation, that the project/product complies with requirements.

Validation	Process used to assure the requirement set is complete and consistent, and that each requirement is achievable.
Verification	Process used to ensure that the selected solutions meet specified requirements and properly integrate with interfacing products.

3 APPLICABLE DOCUMENTS

The documents listed in Section 3.1 are primary to the organization and specification of the LAT Calorimeter subsystem and its interfaces. References in Sections 3.2 through 48 provide key references, test specifications, plans and procedures, and other technical documentation relevant to the design of the calorimeter.

Documents that are relevant to the development of the GLAST mission concept and its requirements include the following:

3.1 CAL Specifications

1. LAT-MD-00044, Memorandum of Agreement – French Participation in GLAST
2. LAT-MD-00081, Memorandum of Agreement – Swedish Participation in GLAST
3. LAT-MD-00098, LAT Calorimeter Program Implementation Plan
4. LAT-SS-00018, LAT CAL Subsystem Specification – Level III Specification
5. LAT-SS-00210, LAT CAL Subsystem Specification – Level IV Specification
6. LAT-SS-00240, CAL Pre Electronics Module (PEM) Specification
7. LAT-SS-00241, CAL PEM Structure Requirements
8. LAT-SS-00239, Calorimeter CsI Detector Element Specification
9. LAT-DS-00095, LAT Calorimeter CsI Crystal Specification
10. LAT-DS-00072, Specification for the Calorimeter PIN Photodiode Assembly
11. LAT-DS-00209, Specification for the Calorimeter PIN Photodiode Assembly (Flight Units)
12. LAT-SS-00211, Specification for the Calorimeter Photodiode Flexible Cable
13. LAT-SS-00087, Calorimeter Electronics System – Conceptual Design
14. LAT-SS-00088, Calorimeter Front End Electronics ASIC – Conceptual Design
15. LAT-SS-00089, Calorimeter Front End Electronics ASIC Specification
16. LAT-SS-00208, Calorimeter Readout Control ASIC – Conceptual Design
17. LAT-SS-00272, Calorimeter Grounding and Shielding Plan
18. LAT-SS-00231, Calorimeter Performance Acceptance Standards and Tests
19. LAT-SS-00238, Calorimeter Subsystem – LAT Instrument Interface Control Document
20. LAT-MD-00220, LAT Calorimeter CsI Crystal Quality Assurance Provisions
21. LAT-MD-00236, Calorimeter Risk Management Plan
22. LAT-MD-00228, Calorimeter Contamination Control Plan

3.2 GLAST References

23. Response to AO 99-OSS-03. “GLAST Large Area Telescope, Flight Investigation: An Astro-Particle Physics Partnership Exploring the High-Energy Universe.” Volume 1: Scientific and Technical Plan. Foldouts: A, B, C, D.
24. GSFC 433-SRD-0001, “GLAST Science Requirements Document”, P.Michelson and N.Gehrels, eds., July 9, 1999
25. LAT-SS-00010, “LAT Instrument Performance Specification.”

26. GSFC 433-SPEC-001, "GLAST Project Mission System Specification," April 24, 2001
27. GSFC 433-IRD-0001, "GLAST Science Instrument – Spacecraft Interface Requirements Document", Draft July 14, 2000
28. GSFC 433-MAR-0001, "Mission Assurance Requirements (MAR) for Gamma-Ray Large Area Telescope (GLAST) Large Area Telescope (LAT)", June 9, 2000
29. GSFC 433-RQMT-0005, "GLAST EMI Requirements Document."
30. GSFC 433-OPS-0001, "GLAST Operations Concept", Sept 7, 2000
31. LAT-SS-00047, "LAT Mechanical Performance Specification."
32. LAT-MD-00099, "LAT EEE Parts Program Control Plan," March 2001
33. LAT-MD-00039, LAT Performance Assurance Implementation Plan
34. LAT-MD-00033, "LAT Work Breakdown Structure," May 9, 2001
35. LAT-TD-00125, "LAT Mass and Power Allocation Recommendations"
36. "Gamma Ray Large Area Space Telescope Instrument Technology Development Program", NRA 98-217-02, NASA Office of Space Science, January 16, 1998.

3.3 Calorimeter Assembly & Test Specifications, Plans, Procedures

37. LAT-SS-00222, Calorimeter Module Assembly, Test and Calibration Requirements
38. LAT-SS-00262, Calorimeter Module Assembly and Test Plan
39. LAT-SS-00258, Calorimeter PEM Assembly Plan
40. LAT-SS-00260, Calorimeter CsI Detector Element Verification Plan
41. LAT-SS-00259, Calorimeter PEM Verification Plan
42. LAT-SS-00257, Calorimeter Mechanical Structure Verification Plan
43. LAT-SS-00096, Calorimeter Crystal Optical Test Bench Requirements
44. LAT-SS-00097, Calorimeter Crystal Mechanical Test Bench Requirements
45. LAT-DS-00255, Calorimeter Crystal Optical Test Bench ADC Control Design Description
46. LAT-SS-00108, Calorimeter Crystal Optical Test Bench Software Requirements
47. LAT-PS-00254, Calorimeter Crystal Optical Test Bench Operating Procedure
48. LAT-SS-00256, Calorimeter PEM Test Bench Specification
49. LAT-SS-00269, VM1 Fabrication and Assembly

3.4 LAT and Calorimeter Supporting Documentation

50. LAT-DS-00038, LAT Mechanical Systems – LAT Layout Drawing
51. LAT-DS-00233, LAT Mechanical Systems – CAL-LAT Interface Drawing
52. Calorimeter VM2 Mechanical Drawings
53. LAT-TD-00229, Report on First Crystal Delivery from Amcryst H
54. LAT-TD-00235, Calorimeter Failure Modes and Mitigation
55. LAT-TD-00243, Calorimeter VM1 Vibration Test Report
56. LAT-TD-00245, CAL Trigger Study
57. Calorimeter WBS Dictionary, July 13, 2001
58. Effect of Air Gap on CsI Light Yield, 30 March 2001
59. Crystal Tests, Joint NRL and Ecole Polytechnique, 30 January 2001
60. Measurements of Analog to Digital Converter Differential Non-Linearity, 24 January 2001
61. Measurements of Circuit Board Induced Noise into Parallel Mounted PIN Diode, 23 January 2001
62. Interface Control Document Between the BFEM Calorimeter (NRL) and the TEM Board (Stanford) Supporting the GLAST Balloon Flight, 12 January 2001

63. Americium calibration of electron yields in BTEM crystals, NRL SEM 2000-01, 14 Sep 2000
64. GCR Rates for Palestine Balloon Flight, 29 November 2000
65. Effect of Light Tapering on Light Yield, 20 October 2000
66. Beam Test Calorimeter Assembly Procedure, 15 May 1999
67. Digitization Error and Position Resolution, 21 April 1998
68. Particle Backgrounds, revised 3 Nov 1997
69. On-orbit Calibration, 10 September 1997 (revised Nov 1998)

4 INTRODUCTION

GLAST is a next generation high-energy gamma-ray observatory designed for making observations of celestial gamma-ray sources in the energy band extending from 20 MeV to more than 300 GeV. It follows in the footsteps of the Compton Gamma Ray Observatory EGRET experiment, which was operational between 1991-1999. The GLAST Mission is part of NASA's Office of Space and Science Strategic Plan, with launch anticipated in 2005. The principal instrument of the GLAST mission is the Large Area Telescope (LAT) that is being developed jointly by NASA and the US Dept. of Energy (DOE) and is supported by an international collaboration of 26 institutions lead by Stanford University.

The GLAST LAT is a high-energy pair conversion telescope that has been under development for over 7 years with support from NASA, DOE and international partners. It consists of a precision converter-tracker, CsI hodoscopic calorimeter, plastic scintillator anticoincidence system and a data acquisition system. The design is modular with a 4×4 array of identical tracker and calorimeter modules. The modules are $\sim 38 \times 38$ cm. Figure 1 shows the LAT instrument concept.

4.1 LAT Science Requirements

The GLAST science requirements are given in Reference 24. An updated set of requirements, as they pertain to the LAT science instrument, are specified in Reference 25. General constraints and requirements on the instrument design are specified in GLAST mission documents (References 26, 27 and 30). The flowdown of the science requirements and instrument constraints to the LAT design is

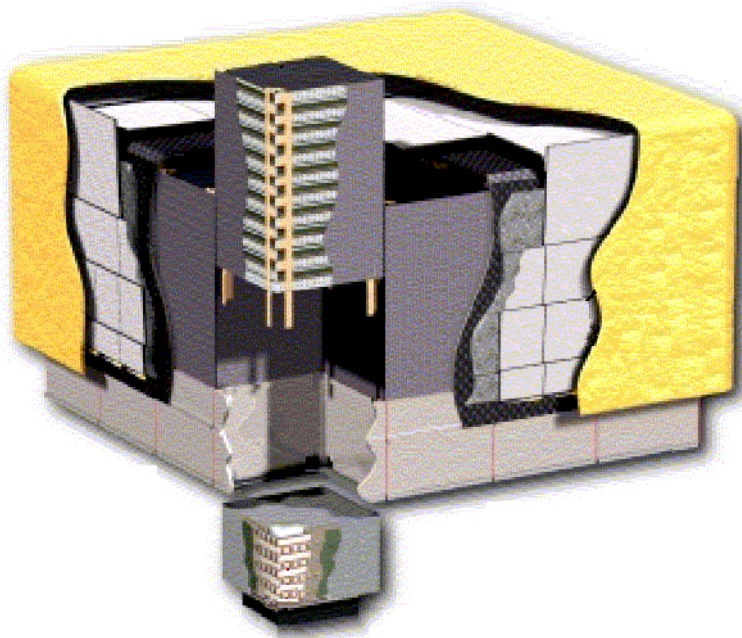


Figure 1. View of the LAT Science Instrument with one Tracker tower module and one Calorimeter module pulled away from the Grid. GLAST is a 4×4 array of identical Tracker and Calorimeter modules.

summarized in Foldout-D of our NASA proposal (Reference 23).

The requirements that most strongly impact the calorimeter design are those pertaining to the energy measurement domain, the energy resolution, background rejection, and the dead time.

4.2 LAT Technical Description

The LAT science instrument consists of an Anti Coincidence Detector (ACD), a silicon-strip detector Tracker (TKR), a hodoscopic CsI Calorimeter (CAL), and a Trigger and Data Flow system (T&DF). The principal purpose of the LAT is to measure the incidence direction, energy and time of cosmic gamma rays while rejecting background from charged cosmic rays and atmospheric albedo gamma rays and particles. The data, filtered by onboard software "triggers", are streamed to the spacecraft for data storage and subsequent transmittal to ground-based analysis centers. The Tracker provides the principal trigger for the LAT, converts the gamma rays into electron-positron

pairs, and measures the direction of the incident gamma ray from the charged-particle tracks. It is crucial in the first levels of background rejection for providing track information to extrapolate cosmic-ray tracks to the ACD scintillator tiles, and it is important for further levels of background analysis due to its capability to provide highly detailed track patterns in each event.

The primary tasks of the GLAST calorimeter are to provide an accurate measure of the energy of the shower resulting from pair conversion of incident gamma rays in the tracker, and to assist with cosmic-ray background rejection through correlation of tracks in the silicon tracker with the position of energy deposition in the calorimeter. The calorimeter also provides triggers to the LAT, particularly for very large energy depositions.

4.3 Calorimeter Design Overview

The Calorimeter (CAL) subsystem consists of 16 identical modules arranged in a 4×4 array that is defined by the LAT support grid structure. The modules mount within the bays of the grid as seen in Figure 1. As a result of the LAT technology development program, we selected a segmented thallium-doped cesium iodide, CsI(Tl), scintillation crystal calorimeter. This technology is well established in both laboratory and space experiments and can meet or exceed all of the identified requirements for the GLAST mission. It provides excellent intrinsic energy resolution at modest cost, provides a fairly fast signal, and is reasonably radiation hard. CsI(Tl) is also a much more rugged material than NaI(Tl) and is

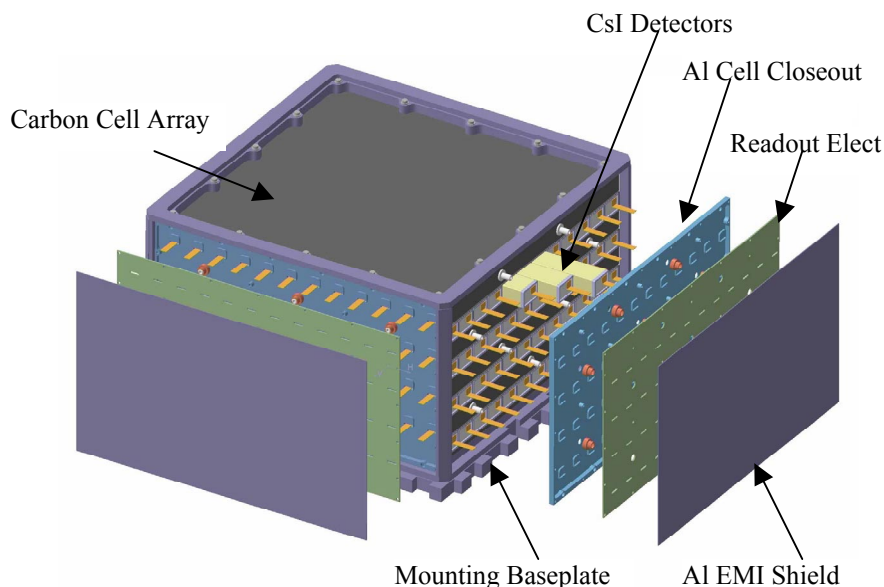


Figure 2. Exploded view of a single Calorimeter module. Eight layers of 12 CsI Crystals are readout by PIN photodiodes and electronics on the four module sides.

comparatively not hygroscopic, greatly reducing the cost and complexity of construction and handling.

To achieve the required energy coverage and resolution, the calorimeter is 8.5 radiation lengths ($8.5 X_0$) deep. An additional depth of $1.5 X_0$ resides in the tracker. To assist in track correlation for background rejection and to improve the energy measurement by shower profile fitting, the calorimeter is segmented into discrete detector elements and arranged into a hodoscopic or imaging configuration and read out using PIN photodiodes. Each CAL module contains 96 crystals of size $26.7 \text{ mm} \times 19.9 \text{ mm} \times 333 \text{ mm}$. The crystals are individually wrapped for improved light collection and optical isolation, and are arranged horizontally in 8 layers of 12 crystals each. Each layer is aligned 90° with respect to its neighbors, forming an x - y array. (See Figure 6 for clarity.)

The spectral response of the PIN photodiodes is well matched with the scintillation spectrum of CsI(Tl), which provides for a large primary signal ($\sim 5,000$ electrons collected in 1.5 cm^2 diode per MeV deposited), with correspondingly small statistical fluctuations and thereby high intrinsic spectral resolution. The PIN

photodiodes are mounted on both ends of a crystal and measure the scintillation light at each end of a crystal from an energy deposition in the crystal. This provides a redundancy in the energy measurement. However, the difference in light levels seen at the two ends of the crystal also provides a determination of the position of the energy deposition along the CsI crystal. The position resolution of this imaging method ranges from a few millimeters for low energy depositions (~ 10 MeV) to a fraction of a millimeter for large energy depositions (>1 GeV).

The size of the CsI crystals has been chosen as a compromise between electronic channel count and desired segmentation within the calorimeter. The indicated size is comparable to the CsI radiation length (1.86 cm) and Moliere radius (3.8 cm) for electromagnetic showers. The size of the crystals is not the dominant factor in determining the imaging capabilities of the calorimeter; most of the positional information is provided by the light-difference measurement.

The hodoscopic array of CsI crystals are installed in a carbon composite cell structure. This structure is surrounded by aluminum top and base plates and side aluminum panels. The side panels hold the CsI crystals in the cells, provide mounting space for the readout electronics printed circuit cards and provide EMI shielding. The baseplate provides for the mounting of the calorimeter module to the LAT GRID structure and is integral to the strength of the GRID.

As shown in Figure 2, the readout electronics for the calorimeter are mounted on the four sides of the module where they attach to the PIN photodiodes. The major design challenges for the calorimeter electronics were

- performing spectroscopic measurements over a dynamic range of 5×10^5 ,
- reducing the power consumption per CsI crystal,
- and minimizing the processing deadtime.

The large dynamic range is supported by dividing the dynamic range into two independent signal chains. A custom dual PIN

photodiode assembly is used at each end of the crystals. The active areas of the two diodes have a ratio of 6 to 1 – the larger area diode covers the low energy band, while the smaller diode covers the higher energy band. The low energy signal covers the energy range from 2 MeV to 1.6 GeV. The high-energy signal chain covers the range from ~ 15 MeV to 100 GeV. The significant overlap between the two ranges permits cross-calibration of the electronics. Each diode has dedicated preamp and shaping amplifiers that are part of a custom application specific integrated circuit (ASIC).

The power for the readout electronics has been reduced by the development of analog and digital CMOS ASICs that are optimized to the performance requirements of the calorimeter.

To minimize event readout dead time, commercial, off-the-shelf (COTS) successive approximation analog to digital converters (ADCs) are used to digitize the pulse amplitude signals from the ASICs. Each crystal end has its own ADC so that the required 192 conversions are performed simultaneously. The digitized energy measurements from each crystal end are transmitted to the Tower Electronics Module (TEM) mounted on the baseplate of the calorimeter modules. The TEM compresses and formats the calorimeter measurements into an event message that is transmitted to the Trigger and Data Flow (T&DF) data processing system.

5 CALORIMETER SUBSYSTEM ORGANIZATION

The calorimeter development is a collaboration among the Naval Research Laboratory (NRL), the Commissariat à l'Energie Atomique / Département d'Astrophysique, de Physique des Particules, de Physique Nucléaire et de l'Instrumentation Associée (CEA/ DSM/ DAPNIA), Centre National de la Recherche Scientifique / Institut National de Physique Nucléaire et de Physique des Particules (IN2P3) in France, the Royal Institute of Technology (KTH) and Stockholm University in Stockholm,

Sweden, and Stanford University-Stanford Linear Accelerator Center (SU-SLAC).

The French institutions involved in the GLAST LAT Calorimeter are CEA/DSM/DAPNIA (hereafter Saclay) and three laboratories associated with IN2P3: PCC of Collège de France, LPNHE of Ecole Polytechnique and CENBG of Université de Bordeaux. The Swedish institutions involved in the Calorimeter are the Royal Institute of Technology (KTH) and Stockholm University in Stockholm, Sweden. The U.S. institutions involved in the GLAST LAT Calorimeter are the Naval Research Laboratory (NRL) and the Stanford Linear Accelerator Center (SLAC).

NRL is the lead institution for the LAT Calorimeter subsystem and has overall responsibility for the Calorimeter Subsystem by direction of Peter F. Michelson, the Instrument Principal Investigator (IPI). NRL's responsibility to NASA is identified, with management oversight and concurrence from P.F. Michelson, in NASA DPR S-15633-Y.

W. Neil Johnson of NRL, Calorimeter

Subsystem Manager, has overall responsibility for the Calorimeter Subsystem of the GLAST LAT instrument. Paolo Carosso, NRL/Swales, is the Calorimeter Project Manager. Isabelle Grenier of the University of Paris VII and CEA Saclay is the French Principal Investigator. Arache Djannati-Ataï of IN2P3-Collège de France is the French Co-Principal Investigator. The French PI and Co-PI have overall responsibility for the GLAST LAT program in France. The French Project Manager, Didier Bédérède of CEA Saclay, is responsible for all decision-making and authority with regard to management of technical, cost, and schedule issues concerning the LAT calorimeter activities in France.

Per Carlson of the Royal Institute of Technology and Stockholm University is the Swedish Principal Investigator.

Figure 3 provides a display of the calorimeter program organization.

CAL development requires well-coordinated interaction and teamwork among the collaboration's project offices. The details of

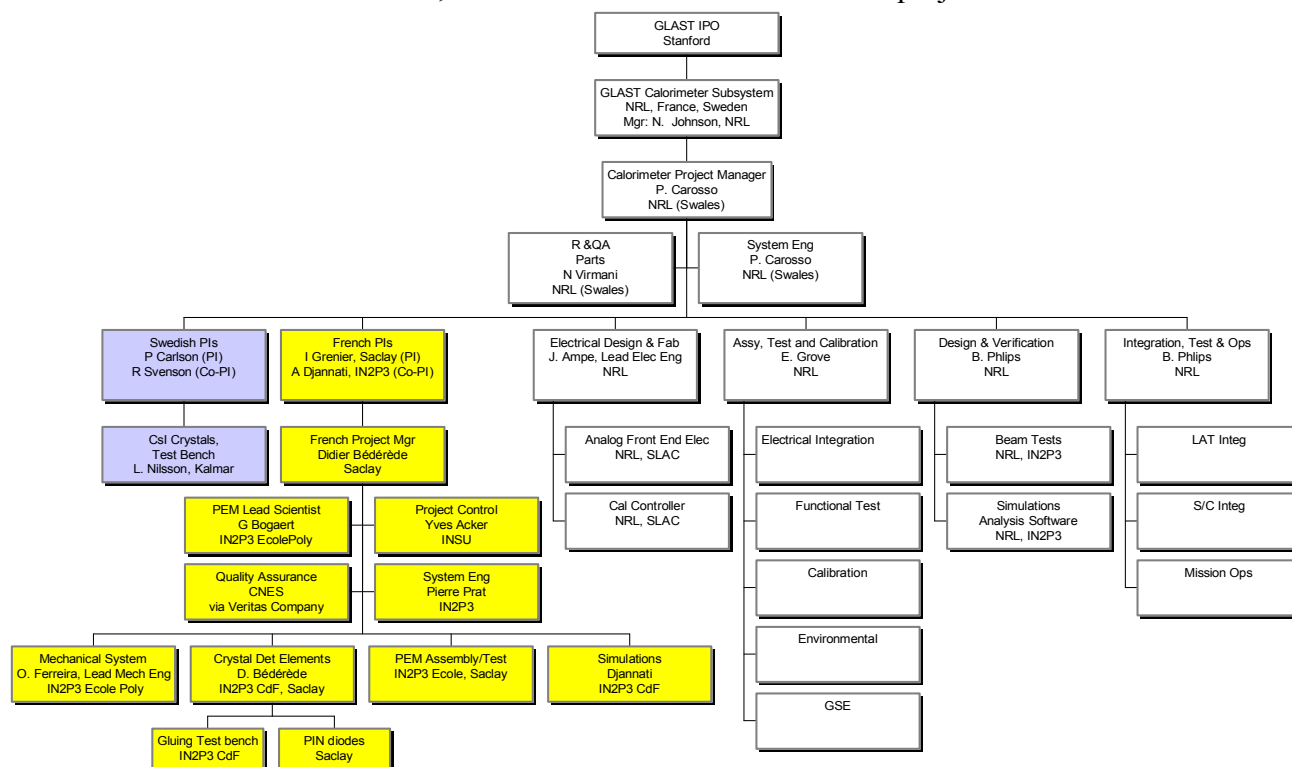


Figure 3. Organization chart for the LAT Calorimeter Subsystem

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the day-to-day management and technical work Calorimeter Program Implementation Plan, practices are documented in the LAT LAT-MD-00098.

6 CALORIMETER SUBSYSTEM WBS

A detailed LAT Work Breakdown Structure is given in Reference 34. The current detailed Calorimeter subsystem WBS Dictionary is provided in Reference 57. Table 1 provides a top-level summary of the Calorimeter WBS to Level 5 and identifies responsible institution(s).

Table 1. Calorimeter Subsystem Work Breakdown Structure

WBS	Task	Responsibility
4.1.5	Calorimeter	
4.1.5.1	Calorimeter Management	NRL
4.1.5.1.1	Program Management and Administration	NRL, CEA Saclay
4.1.5.1.2	Configuration & Document Management	NRL
4.1.5.1.3	Program & Design Reviews	
4.1.5.1.4	Travel	
4.1.5.1.5	Science	
4.1.5.2	Systems Engineering	NRL
4.1.5.2.1	Calorimeter System Requirements and Specs	
4.1.5.2.2	Allocation and Margin Mgmt.	
4.1.5.2.3	System Verification	
4.1.5.3	Mission Assurance	NRL
4.1.5.3.1	Reliability	
4.1.5.3.2	Safety	
4.1.5.3.3	Flight Assurance	
4.1.5.4	Calorimeter Design	NRL
4.1.5.4.1	Calorimeter Instrument Design	NRL
4.1.5.4.2	Structure	NRL
4.1.5.4.3	Thermal Design	NRL
4.1.5.4.4	Power	NRL
4.1.5.4.5	Simulations	NRL
4.1.5.5	CsI Detector Elements (CDE)	NRL, IN2P3 Ecole
4.1.5.5.1	CDE design	IN2P3 Ecole
4.1.5.5.1.1	PIN optical coupling	IN2P3 CdF
4.1.5.5.1.2	Dual PIN Photodiodes performance tests	CEA-Saclay
4.1.5.5.1.3	Crystal performance & wrapping study	IN2P3 Ecole CEA Saclay
4.1.5.5.2	CsI(Tl) Scintillation Crystals	KTH Sweden
4.1.5.5.3	Dual PIN photoDiode (DPD)	Saclay
4.1.5.5.4	Dual PIN Photodiode Interconnect	NRL, CEA Saclay

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4.1.5.5.5	CDE I&T	IN2P3/CEA-Saclay
4.1.5.6	Pre-Electronics Module (PEM)	NRL, IN2P3 Ecole
4.1.5.6.1	PEM Structure Fabrication & Test	IN2P3 Ecole
4.1.5.6.2	PEM Assembly & CDE Insertion	IN2P3 Ecole
4.1.5.6.3	PEM GSE	IN2P3 Ecole
4.1.5.6.4	PEM Assembly Facilities	IN2P3 Ecole
4.1.5.6.5	PEM Delivery to NRL	CEA-Saclay
4.1.5.6.6	PEM Acceptance at NRL	NRL
4.1.5.7	Analog Front End Electronics	NRL
4.1.5.7.1	AFEE Design	NRL
4.1.5.7.2	ASIC Development	NRL, SLAC
4.1.5.7.3	GCFE Test Board	NRL
4.1.5.7.4	VM Front End Electronics	
4.1.5.7.5	EM Front End Electronics	
4.1.5.7.6	Flight Front End Electronics	
4.1.5.7.7	GSE for AFEE Test	
4.1.5.8	Calorimeter Tower Controller	NRL, SLAC
4.1.5.8.1	Design	
4.1.5.8.2	Fabrication	
4.1.5.8.3	Test	
4.1.5.9	Calorimeter Module Assembly, Test & Calibration	NRL
4.1.5.9.1	Engineering Model	
4.1.5.9.2	Flight Modules	
4.1.5.9.3	Cal Module GSE	
4.1.5.9.4	Cal GSE SW	
4.1.5.A	Instrument I&T Support	NRL
4.1.5.A.1	Instrument Integration Support	NRL
4.1.5.A.2	Calibration Units	NRL, IN2P3 CENBG
4.1.5.A.3	Instrument Test Support	NRL, IN2P3
4.1.5.B	S/C Integration Support	NRL
4.1.5.C	Mission Operations Support	NRL

7 CALORIMETER SUBSYSTEM DELIVERABLES

The Calorimeter subsystem will deliver the following items to the project:

1. Calorimeter module mechanical and thermal finite-element models.
2. Engineering Model, delivered to the I&T group, after completion of Calorimeter subsystem testing and calibrations
3. One qualification-unit Calorimeter module.
4. 16 flight-unit Calorimeter modules.
5. One flight-spares Calorimeter module.
6. Storage containers for all 19 Calorimeter modules.
7. Mechanical ground support equipment for module handling and installation.
8. Design documentation and as-built documentation for the 18 tower modules, including the fabrication database.
9. A preliminary calibration database for each calorimeter module.
10. The Calorimeter operating and handling manual.

8 REQUIREMENTS AND SPECIFICATIONS

The Calorimeter Subsystem requirements and specifications are found in the Calorimeter Subsystem Level III Specification (Reference 4 in Section 3.1). It specifies the calorimeter requirements necessary to meet the overall LAT system performance (Reference 25 in Section 3.2). The Calorimeter Level III Specification was formally reviewed on March 28, 2001. Table 2 is a summary of the most important level III requirements.

The Level III CAL trigger requirements are met using a combination of energy discriminators in the CAL electronics and Boolean processing in the TEM's CAL controller. Simulations indicate that a simple "OR" of CAL logs with 100 MeV discrimination will have a 93%

Table 2. Calorimeter Subsystem Level III Requirements Summary

Parameter	Requirement
Energy Range	5 MeV – 300 GeV 1 MeV – 1 TeV (goal)
Energy Resolution	< 20% (5 MeV < E < 100 MeV) < 10% (100 MeV < E < 10 GeV) < 6% (10 GeV < E < 300 GeV, incidence angle > 60 deg)
Design	Modular, hodoscopic, CsI > 8.4 RL of CsI on axis
Active Area	>1050 cm ² per module < 16% of total mass is passive mtrl.
Position Resolution	<1.5 cm in 3 dims, min ionizing particles, incident angle < 45 deg.
Angular Resolution	7.5 × cos(θ) deg, for cosmic muons in 8 layers
Dead Time	< 100 μs per event < 20 μs per event (goal)
Low Energy Trigger	>90% efficiency for 1 GeV photons traversing 6 RL of CsI < 2 μs trigger latency
High Energy Trigger	>90% efficiency for 20 GeV photons depositing at least 10 GeV < 2 μs trigger latency
Size (module)	< 364 mm in width (stay clear) < 224.3 mm in height (stay clear)
Mass	< 1492 kg (93.25 kg/module)
Power	< 91 Watts (conditioned) (5.69 W/module)
Instrument Lifetime	>5 yrs, with no more than 20% degradation.

efficiency to 1 GeV photons for the Low Energy Trigger requirement.

The CAL high energy trigger utilizes the "three in a row" concept of Tracker trigger and requires discriminators set at about 1.1 GeV. This configuration has efficiency greater than 90% for 20 GeV photons but gives an acceptable 14 Hz rate from cosmic ray background protons in Level 1 triggers. Level 2 processing reduces this rate to 0.5 Hz. This result is described in greater detail in Ref 9.

The Calorimeter Level IV specifications (Reference 5) are derived for the specific implementation of the LAT calorimeter and its interface requirements to other LAT subsystems. In this implementation, the major

components of the calorimeter subsystem and their specifications are:

- CAL Pre Electronics Module (PEM) Specification, LAT-SS-00240
- CAL Structure Requirements, LAT-SS-00221
- Calorimeter CsI Detector Element Specification, LAT-SS-00239
- LAT Calorimeter CsI Crystal Specification, LAT-DS-00095
- Calorimeter PIN Photodiode Assembly

Specification (Flight Units), LAT-DS-00209

- Calorimeter Electronics System – Conceptual Design, LAT-SS-00087
- Calorimeter Front End Electronics ASIC – Conceptual Design, LAT-SS-00088
- Calorimeter Front End Electronics ASIC Specification, LAT-SS-00089
- Calorimeter Readout Control ASIC – Conceptual Design, LAT-SS-00208

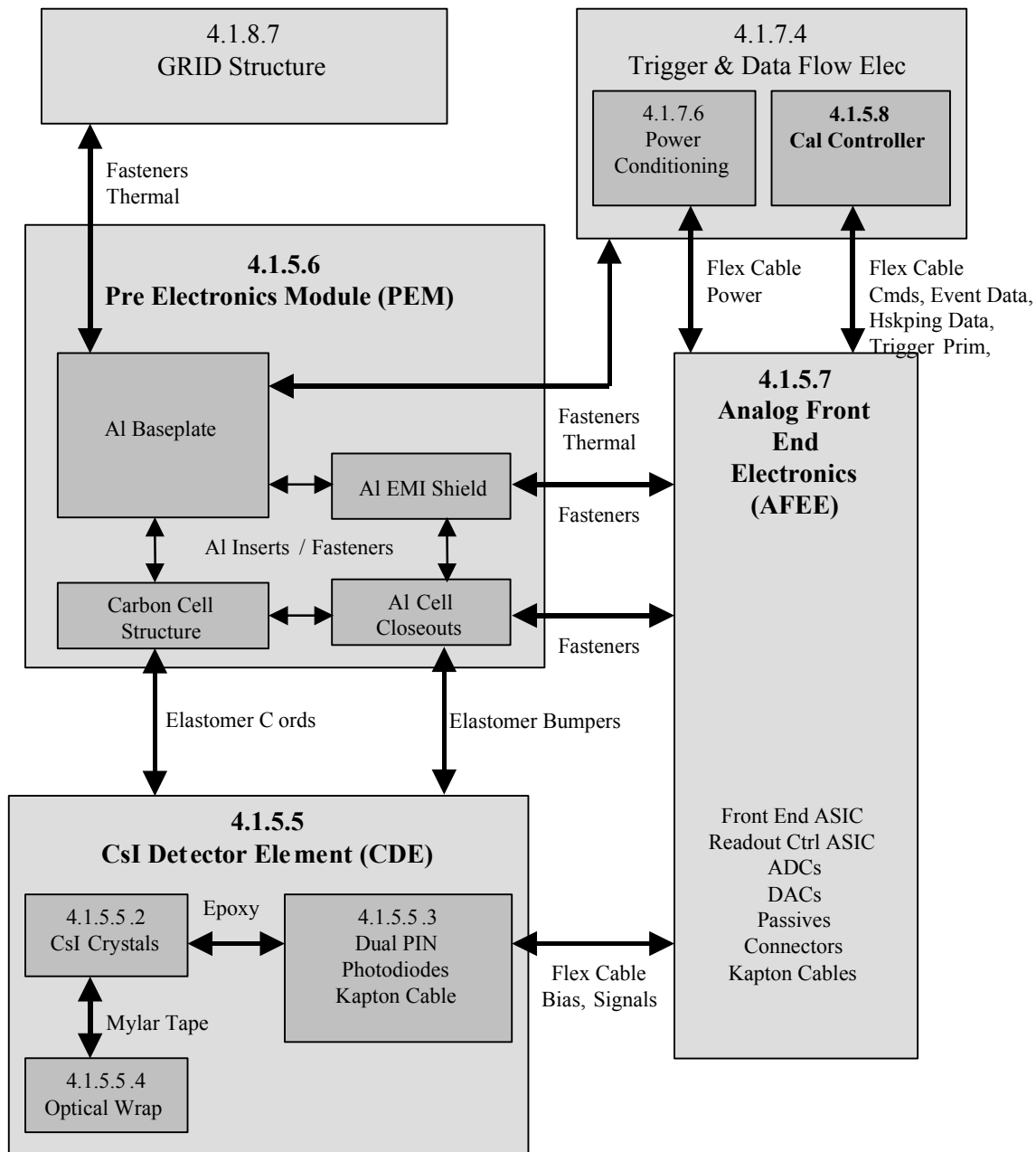


Figure 4. Block diagram of the calorimeter subsystem with internal and external interfaces
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Table 3. Calorimeter Mass Allocation.

	Mass (kg)
SRR Est. (Adj.)	1482.1
ANSI/ AIAA Reserve Recom'd	101.8
Subsystem Reserve Allocation	9.9
Subsystem Budget Allocation	1492.0

The interfaces of the Calorimeter subsystem to the rest of the LAT instrument are specified in the document, “Calorimeter Subsystem – LAT Instrument Interface Control Document, LAT-SS-00238”. These interfaces and the relationships of the various components of the CAL subsystem are shown graphically in Figure 4.

The resources allocated to the calorimeter subsystem are documented in Reference 35 and are summarized below. As shown in Table 3, the baseline calorimeter mass was established at the System Requirements Review at 1482.1 kg. Based on ANSI/AIAA standards a reserve of 101.8 kg was identified, but only 9.9 kg of that reserve have been allocated to the calorimeter. Thus, the calorimeter is designing to a mass limit of 1492 kg. Exceeding this limit requires configuration control board allocation from the mass reserve.

Table 4 shows a similar summary for the conditioned power allocated to the calorimeter. The calorimeter is allocated 91 watts of conditioned power.

9 CALORIMETER DEVELOPMENT AND PROTOTYPING

Multiple calorimeter prototypes were built during the SR&T and ATD phases of the GLAST program, starting in 1995. The original calorimeter consisted of a two-dimensional

Table 4. Calorimeter Power Allocation

	Power (Watts)
SRR Est. (Adj.)	87.0
ANSI/ AIAA Reserve Recom'd	12.0
Subsystem Reserve Allocation	4.0
Subsystem Budget Allocation	91.0

array of crystals (with a square cross-section) aligned with the Z-axis of the instrument. This prototype was tested in beam at SLAC in 1996. In 1997, the same crystals were converted into a hodoscopic stack and again tested in beam at SLAC. Table 5 provides a full list of all the prototypes and the associated beams and tests. All prototypes prior to the 1999 prototype used commercial PIN diodes.



Figure 5. Photo of completed beam test calorimeter suspended on its lifting harness. The mounting plate below is part of the shipping container.

Table 5. Summary of Calorimeter Development Beam Tests

Year	Beam	Prototype	Test	Result
1996	SLAC	Longitudinal 3x3x19 cm CsI, commercial diodes, laboratory electronics	First measurements with high energy gamma rays and electrons, no tracker	Demonstrated spectroscopy Tried transverse geometry
1997	SLAC	Hodoscopic 3x3x19 cm CsI, commercial diodes, laboratory electronics	Various energy electron and gamma ray beams First hodoscopic measurements First measurements with tracker	Confirmed hodoscopic imaging and spectroscopy
1998	MSU	SLAC 1997+ new longer, thinner crystals	Protons, helium, and carbon beams	Initial test of cosmic-ray calibration concept
1998	CERN	Long crystals with dual diodes	High energy muon beams	Demonstrated improved light tapering
1999	CERN	3x3x19 cm crystals	High energy electrons	
1999-2000	SLAC	Full size prototype Custom ASICs Flight-grade mechanical structure	Electron, proton, and photon beams First test with full prototype "tower"	Demonstrated GLAST AO-level performance
2000	GSI	Calorimeter from SLAC 1999 tests	Carbon and Nickel beams	Demonstrated calibration with light and heavy elements
2001	Balloon	Tower from SLAC1999	First Flight	Expected in August 2001

9.1 Beam Test Engineering Model

As part of the NASA Advanced Technology Development Program, a full sized prototype of the LAT calorimeter was fabricated and tested in beam tests at SLAC. This Beam Test Engineering Model (BTEM) calorimeter is shown in Figure 5. The module at the time of the technology program was ~33 cm width rather than the ~38 cm size of the LAT instrument.

The mechanical structure for the BTEM calorimeter did not include the carbon composite cell structure that is the flight design, however much was learned about CsI crystal wrapping, PIN photodiode bonding to CsI, and many other issues that relate to the light yield from the CsI detectors in this hodoscopic concept. Figure 6 shows a partial hodoscopic

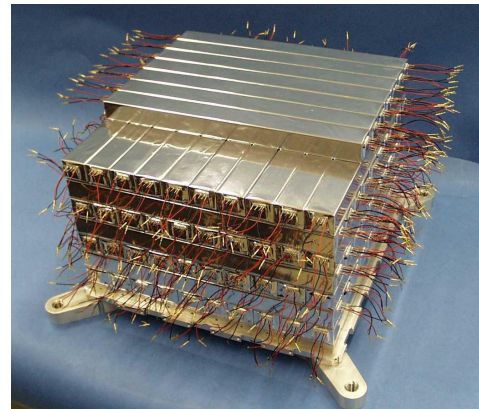


Figure 6. Hodoscopic configuration of CsI crystals in assembly for the BTEM GLAST calorimeter. Crystals are arranged in 8 alternating layers of 10 crystals. PIN photo diodes are mounted on both ends of the CsI crystals.

array of the wrapped CsI crystals with PIN diodes for the BTEM calorimeter.

The readout electronics were mounted on the sides as seen in **Error! Reference source not found.** As in the flight design, analog ASICs process the signals from dual PIN photodiodes bonded on the end of each crystal. COTS ADCs digitize the pulses from the ASICs and the digitized measurements are transmitted to a data acquisition controller mounted on the baseplate of the BTEM.

The large dynamic range of the Calorimeter, $>10^5$, can only be dealt with by having multiple chains, or ranges, of electronics for each crystal. Each electronics range needs an input signal. It was realized early on that the simplest circuitry for additional input signals was the diode of the PIN diode sensors. This approach was tested in-beam in 1998. After considering the possibility of two or three diodes, we settled on a concept with two diodes feeding two preamplifiers, each of which would feed two different gain amplifiers. For convenience, the two diodes would be mounted on a single carrier. The two diodes would consist of separate pieces of silicon and would be grounded separately to minimize cross-talk. Since the signal amplitude is roughly proportional to the area of the PIN diode, the ratio of diode areas can be used to tune the gain of the various ranges. However, this would put extremely stringent requirements on the allowable cross-talk between the diodes. We therefore chose to only allow a moderate ratio of areas and to make up the remainder of the difference in gain in the electronics.

The smaller diode area was selected to be the minimal area that could generate signals sufficient to detect cosmic ray muons when read out with laboratory electronics. This area is $\sim 25 \text{ mm}^2$. The large-area diode needs to be large enough to achieve the low-energy requirements of the calorimeter. Since the capacitance of the diode is proportional to its area, the noise of the front-end electronics will also be proportional to the area. However, the CMOS electronics

required for GLAST have a relatively large noise floor, therefore allowing a relatively large area without generating much additional noise. The total area available for diodes is of course limited by the fraction of the cross section of the crystals not required for mechanical mounting of the crystals themselves, and by the maximal active area possible within a certain size diode carrier.

We started work with Hamamatsu Photonics in 1998 and developed a custom dual photodiode for the 1999 Beam Test prototype. The two diodes have area 24 and 96 mm^2 , generating a gain ratio of 4. Using the Hamamatsu design rules, the dual PIN diode ceramic carrier needed and area of 15.5 mm by 16.5 mm. An example of these diodes can be seen in Figure 7.

9.2 LAT Prototyping

9.2.1 Vibration test of VM1

The VM1 was loaded with 93 steel logs (with slots to reduced weight to 1 kg) and 3 CsI logs. The crystals had been previously optically tested at Saclay and cross-checked at Ecole Polytechnique.

All the logs were mounted inside the cells with 4 silicone rubber bands (see Figure 8). A simple tooling has been used to ease the insertion,

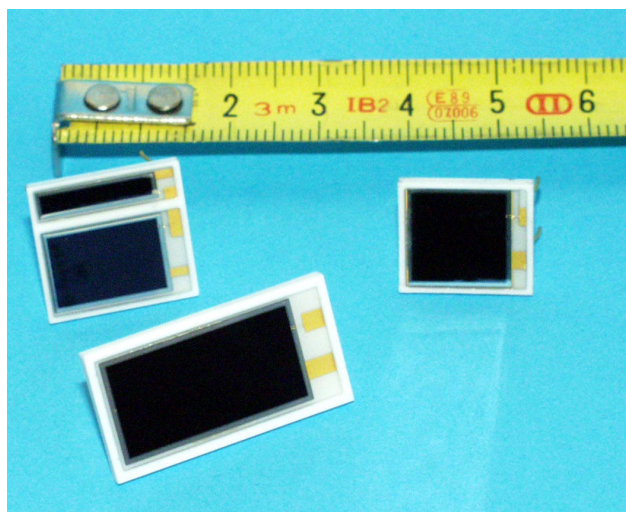


Figure 7. PIN photodiodes used in testing. Custom dual diode from ATD program and Commercial 1 and 2 cm^2 diodes.



Figure 8. Insertion of dummy logs into VM1 carbon cell structure.

mainly to hold the rubber bands stretched.

The vibration test consisted of sine sweep, sine burst and random tests along 2 axes, with qualification levels. The model was fixed on a rigid aluminum frame so that support was only provided on the perimeter of the bottom plate. The attachment was similar to what is foreseen for the interface with the grid, except for the tabs (see Figure 11). The first vibration frequencies were measured at 115 Hz for transverse axis and 185 Hz for vertical axis.

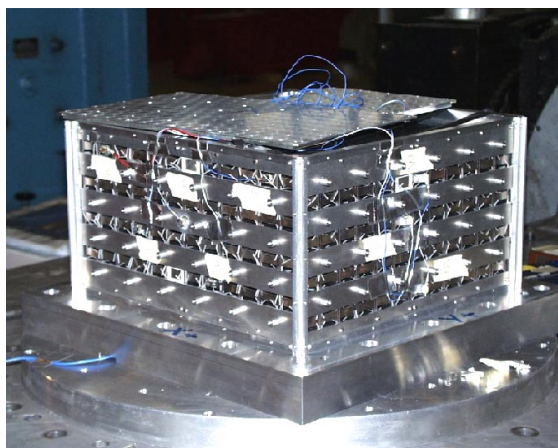


Figure 11. Instrumentation of VM1 for vibration test (December 2000)

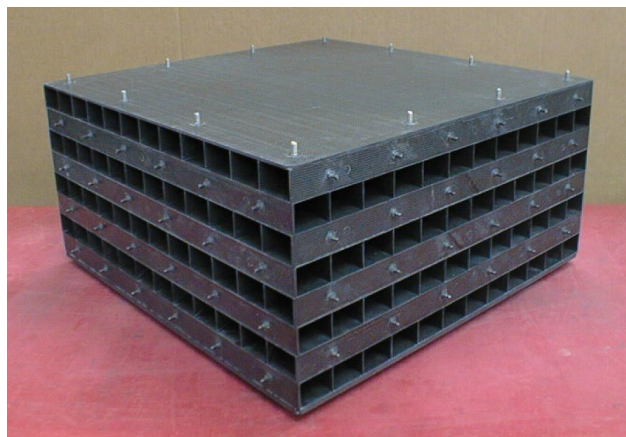


Figure 9. Carbon composite cell structure for VM1.

9.2.2 Absolute light yield

We measured the absolute light yield, i.e. the number of electrons collected in the 1-cm² PIN per MeV deposited in the crystal, for various wraps and sleeve linings. We used a nuclear line source to provide an absolute energy (²²⁸Th at 2.61 MeV), and we calibrated the electronic gain scale. We employed three methods to calibrate the gain scale: we illuminated the PIN directly with an ²⁴¹Am source; we injected charge into a calibrated capacitor attached to the signal input on the preamp; and we injected

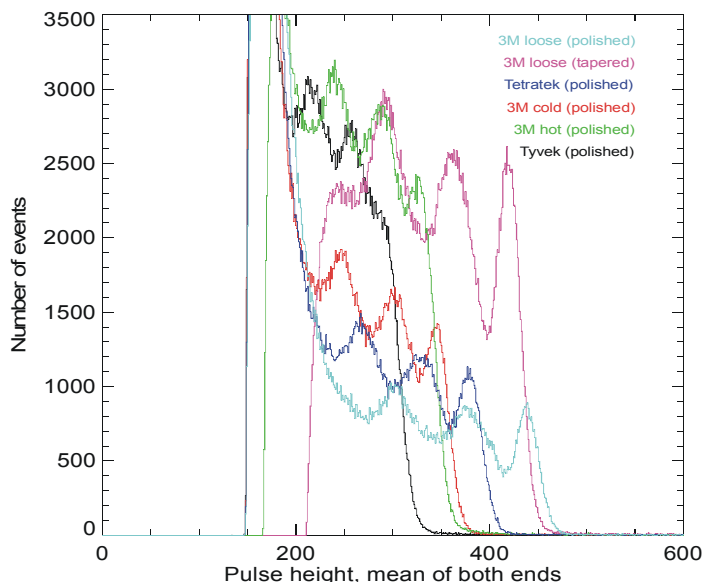


Figure 10: Spectra of ²²⁸Th for various wraps or sleeve linings. The 2.61 MeV photopeak and first and second escape peaks are visible. Entries in the legend are ordered by increasing photopeak, from bottom to top.

Wrap or lining	2.6 MeV peak	Yield (e/MeV)
3M loosely wrapped	435	5300
Tetratex + adhesive aluminized Mylar	380	4630
3M cold	345	4200
3M hot	320	3900
Tyvek	290	3530
3M loosely wrapped, after light tapering	420	5120

Table 6: Light yields with various crystal wraps or sleeve linings for the IN2P3 Crismatec crystal. The location of the 2.6 MeV peak (in pedestal-subtracted ADC bins) is the average of the two ends

charge into the test input of the preamp.

We compared the absolute scintillation light yield for a number of configurations, summarized in Table 6. Figure 10 shows the spectrum of the coherent sum of log ends in each configuration. Apart from the Tyvek run, each spectrum clearly shows the 2.61 MeV photopeak and the first and second escape peaks. Each histogram contains 500k events, but the higher discriminator thresholds in the tapered run and the cold cell run result in more counts in the photopeak and escape peaks.

The testing with Tyvek and Tetratex confirm conclusions in BTEM99 prototype development. The new results with the 3M material are quite encouraging. The 3M hot cell gave approximately 10% more light than the

Tyvek. The hot cell did not show the specular reflection characteristic of the bare 3M material, and scattered light observed down the length of the cell seemed to be less intense than down the cold cell. The weave of the composite material was clearly visible, formed into the surface of the 3M material.

The 3M cold cell gave ~10% more light than the 3M hot cell, which perhaps is consistent with its apparent greater brightness in scattered light. We note also that the spray adhesive used to attach the 3M material to the composite cell wall moved the reflective surface into closer contact with the crystal sides than in the 3M hot cell.

The Tetratex + adhesive aluminized Mylar wrapping performed 10% better still, giving 4630 e/MeV, which is fairly consistent with the value we typically observed in the $310 \times 30 \times 23$ mm Crismatec and Amcrys H crystals of the BTEM99 calorimeter in the same wrapping after 10 months under pressure.

The best-performing wrap was the 3M birefringent material loosely wrapped around the crystal, yielding ~25% more light than the Tetratex wrap. It is not clear why this loose wrapping was decidedly superior to the 3M cold cell. Indeed we applied this wrap quite loosely, without creasing the material at the edges of the crystal. The material was free to separate from the long crystal surfaces by up to a few millimeters.

10 CALORIMETER SUBSYSTEM DESIGN

10.1 Mechanical Design - PEM

10.1.1 General description

The mechanical structure consists of carbon composite structure defining cells for 96 CsI Detector Elements (CDE), an Aluminum base plate which presents the structural interface to the LAT Grid structure, Al top plate, Al cell closeout plates and EMI shields on the four sides (see Figure 12). A volume between the cell closeout plates and EMI shields on the four sides houses the analog front end electronics.

The main functionalities of PEM the mechanical structure are to:

- Position the 96 CDEs of a module and hold them so that they are not damaged by the environmental mechanical and thermal loads
- Provide secure fixture for the AFEE boards and guaranty their thermal control
- Efficiently shield the PIN photodiodes and the AFEE boards
- Provide secure fixture for TEM boxes and power supplies and ensure the transfer of the heat dissipated by their electronics into the grid wall.
- Stiffen the base of the grid
- Provide sufficient stiffness to the CAL module so that their first natural frequency is above 100 Hz
- Provide sufficient stiffness to the CAL modules so that they do not deflect by more that 0.5 mm under environmental launch loads

10.1.2 Composite structure

The composite structure consists of an array of 96 carbon fiber epoxy resin composite cells, arranged into 8 layers of 12 cells. Each layer is rotated by 90° in the relation to the neighbors, to define an X – Y orientation for the CsI logs. The main concept that motivates the design is to build a mechanical structure, stiff enough to withstand environmental loads without requiring any contribution from the crystals. The honeycomb type geometry of the structure,

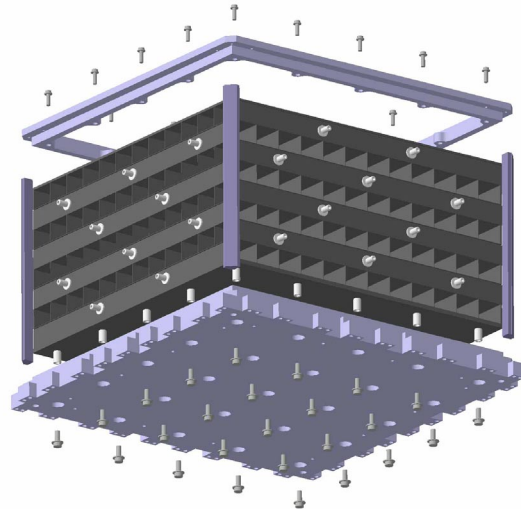


Figure 12. Expanded view of the PEM showing carbon cell structure with Al support structure. Cell closeout panels and EMI shields are not shown.

combined with light, high strength material ensures the required mechanical properties, while minimizing the amount of passive material between the CsI logs. The thickness of the wall within a layer is less than 0.4 mm and from layer to layer less than 0.8 mm. The outer walls are thicker since metallic inserts are embedded in the composite material to provides attachment point for the aluminum parts.

The composite structure is manufactured as a single part from a lay up of prepreg material. A complex aluminum – composite mold is used for this operation. The mold is a modular tooling made of height frames, to which twelve aluminum mandrels are associated, and two solid plates, that act as a base and a cover. The aluminum mandrels are wrapped with prepreg and assembled inside the frames. The frames are next stacked between the base and the cover. A curing cycle ends the process. The accuracy of the structure and the reproducibility are guarantied by the tooling. A final accuracy of ± 0.2 mm is needed to guaranty that the CAL module stay within the stay-clear dimensions.

10.1.3 CDE Mounting

The CDE are mounted independently inside the composite cells and access is granted to each of them until the close out plates are assembled. A

clearance of 0.3 to 0.5 mm allow their integration inside the cells. A silicone elastomeric cord is placed between each the corners of the cells and the chamfers of the crystals to provide a support distributed along the full length of the logs and center the CDE in the cell. The cords are stretched to reduced their diameter and allow the insertion of the log. Transverse vibrations of the CDE are damped by the elastomeric cords. Figure 14, lower right, shows a CDE partially inserted into a carbon cell with the elastomeric cords in the four corners. The figure shows only one carbon cell for clarity; the PEM is actually a single structure of 96 cells.

A silicone elastomeric frame is placed around the photodiodes, between the ends of the logs and the close out plates. The elastomer acts as a stop for longitudinal displacements and damps the longitudinal vibrations. The elastomer will not compress by more than 0.5 mm to avoid any contact between the pins of the photodiode and the bosses of close out plate. Yet, the elastomer must allow the expansion of the logs up to the maximum survival temperature of 50 °C without inducing prohibitive stress in the crystal. The log must be able to expand by at least 0.2 mm at both ends.

The thickness of the elastomeric damper needs to be adjusted to the crystal length to efficiently fulfill both requirements.

10.1.4 Base plate

The Al base plate provides the primary mounting and handling interface for the CAL module. It is fundamental to the strength and stiffness of the LAT Grid structure. The plate is attached to the inserts below the composite structure and to the close out plates and side panels. It connects the module to the Grid via 70 fasteners. The fasteners pass through holes machined on 36 tabs evenly positioned at the perimeter of the plate. Two additional holes are equipped with accurately mounted pins to provide the alignment of the modules on the grid.

To correctly stiffen the grid, the base plate must have the equivalent stiffness of a solid 8 mm aluminum plate. It transfers into the grid the 50 W (TBR) dissipated by the electronic boxes, mounted below the modules, and the 4 W (TBR) dissipated by the 4 AFEE boards.

10.1.5 Close out plates

The Al cell closeout plates contain the CDE in the carbon cell using elastomeric bumpers. The closeouts attach to the carbon cell structure via Al inserts manufactured into the structure. They provide attachment points for the AFEE boards and act as a radiator to collect the power dissipated by each of them and transfer it into the grid via the base plate.

Bosses on the closeout plates provide clearance for the PIN photodiode cable connection and have slits to provide passage of the PIN kapton cable to the analog front end electronics PCB above. The openings in the close out plates are kept to a minimum for efficient EMI shielding.

10.2 CsI Crystals

The CsI scintillating crystals are the responsibility of the LAT collaborators from Sweden. The Swedish consortium has responsibility for procuring, testing, and delivering to France all CsI crystals for the CAL.

10.2.1 Crystal Requirements

The specifications on the CsI crystals were derived from the experience the calorimeter team gained by building prototypes in 1996, 1997 and 1999. The CsI crystal dimensions were changed to accommodate the 4x4 modularity of GLAST, the 8.5 radiation length depth of the calorimeter, and the French mechanical design for holding individual crystals. The specifications are in document LAT-DS-00095 (Reference 9).

The dimensions of the crystals are:

Length 333 mm + 0.0, – 0.6 mm

Width	26.7 mm	+ 0.0, – 0.4 mm
Height	19.9 mm	+ 0.0, – 0.4 mm

The four 333 mm edges are chamfered with a chamfer of 0.7 mm length at an angle of 45 degrees. Careful control of the crystal dimensions and planarity are critical to the ease of assembly of the CDEs into the PEM.

Crystal light yield is specified by the energy resolution at 1.275 MeV (^{22}Na radioactive source) measured by a photomultiplier tube. That energy resolution is better than 13% FWHM. Crystal to crystal variations can not be more than 10% from the mean crystal light yield.

The light yield tapering along the length of the crystal must be monotonic and the end-to-end ratio must be $60 \pm 10\%$; that is, the light collected from the far end of the crystal is 60% of that from the near end.

The light yield of the crystals after 10 kRad of radiation must be greater than 50% of the original yield. This will be verified on CsI boule samples prior to the manufacturing of crystals from that boule.

10.2.2 Crystal Procurement

The consortium advertised a request for bids on December 8, 2000. Three bids were received from two crystal manufacturers by January 22, 2001, the closing date. The manufacturers were Amcrys-H of the Ukraine, and Crismatec of France. Amcrys-H put in a direct bid and a separate bid through a French distributor. All bids indicated the ability to deliver then entire requirement of crystals at the required delivery rate. In late march, the consortium selected the direct bid from Amcrys-H as the winning bid. A contract was signed between the consortium and Amcrys-H on April 8 2001.

The contract specifies the delivery of:

24 crystals	by June 1, 2001
106 crystals	by August 1, 2001, (assuming test equipment was delivered by 31 May, 2001)

110 crystals	by 1 April, 2002
1800 crystals	between 1 July, 2002 and 1 April, 2003, with a minimum of 200 crystals delivered per calendar month.

A slight change in the dimension of the crystals is allowed before March 1, 2002.

The first twenty four crystals have already been delivered by Amcrys-H, satisfying the first deliverable.

10.2.3 Crystal Testing

The consortium is responsible for the acceptance testing of the CsI crystals. This involves among other things the testing the mass of the crystals, the mechanical properties of the crystals, the optical properties of the crystals, and the radiation hardness of the crystals. The consortium is helped in these tasks by a group at the University of Kalmar.

The mass of each log can be checked by a regular scale. The first 24 crystals ranged in mass from 785 to 795 grams, with a mean value of 790 grams.

Mechanical Testing

The mechanical dimensions of each crystals are tested by set of gauges and special fixtures. The mechanical test setup was developed at Kalmar and is specified in document, LAT-DS-00096. The setup consists of a set of six gauges that measure the long surfaces of the crystal as it sits on three reference pins. The crystal is then rotated 90 degrees along its long axis to measure another surface. A separate fixture measures the length of each crystal. To minimize confusion and discrepancies, two copies of these test sets will be used: one in Sweden, and one at the factory in the Ukraine. The first setup is already built and was tested at Kalmar on test crystals and on traceable references. The system was found to be accurate to 10 micron. The setup was used to measure the first 24 crystals delivered in June 2001. The crystals mostly meet the specifications, as described in LAT-TD-00229-01, "Report on First Crystal Delivery

from Amcrys-H". Most surfaces appeared to be convex, although within the specifications. The crystals seemed to be too long, although after correcting for the difference in temperature between the specifications and the measurement, this effect was mostly eliminated. The setup is due to be delivered at the factory in late July, and installed in early August 2001.

Optical Testing

The optical properties of the crystals are measured by a test bench developed by NRL. This test bench has evolved from the test bench used to measure the optical properties of the crystals used for the 1999 prototype. The test bench consists of a pair of photo-multipliers and a movable collimated radioactive source. A photo-multiplier tube is connected to each end of a CsI crystal and the light collected in each photo-multiplier is measured as a function of the position of the radioactive source. The light yield is supposed to be monotonically decreasing away from the end, and the light yield at the far end of a crystal has to be 60 \pm 10 % of the light yield at the near end of the crystal. The light yield must be sufficient to obtain an energy resolution of better than 13% FWHM for the 1275 keV line from Na-22.

The test bench electronics system consists of laboratory NIM electronics, a custom interface board, and a PC. A Labview program controls the test bench, acquires the data, and analyzes the data to derive the desired quantities. Six of these setups are planned: 2 in the Ukraine, 2 in Sweden, 1 in France and one in the US. Two setups are needed at the factory and in Sweden because one would not be sufficient to achieve the required throughput. The first two units were built by NRL, the remaining four are to be built by Sweden. The first bench was shipped to Kalmar in April and has been operating there. The first batch of crystals from Amcrys-H have been tested and the results can be found in the document "Report on First Crystal Delivery from Amcrys-H", LAT-TD-00229-01. Almost

all crystals have the desired light tapering. The crystals that do not meet the specification seem to have no tapering at all, as if this step was not executed on those crystals. All crystals easily met the energy resolution specification.

Radiation Hardness Testing

The radiation hardness tests are to be performed on boule samples from each boule used in the production of GLAST crystals. The boule samples are cylinders of radius 2.5 cm and height 2.5 cm. They will be tested in a Co-60 irradiation facility of the Royal Institute of Technology. The light yield from a boule sample is not to be reduced by more than 50% after irradiation with 10 krad. A two-channel prototype test bench consisting of diodes and hybrid preamplifiers is currently being built at NRL. The test bench will measure pre-and post-irradiation performance.

10.3 PIN Photodiode

The Flight Model PIN photodiodes are similar in design to the diodes developed for the BTEM calorimeter. These diodes are based on the Hamamatsu Photonics standard commercial S3590 PIN diode series. The most significant change from the BTEM design is the increase in the area of the large diode to 150 mm², generating a gain ratio between the large and small diode of 6. The larger area also caused the selection of a thicker depletion depth for the diode – from \sim 200 μ m to 300 μ m.

Table 7. Dual PIN Photodiode Characteristics

	Large PIN	Small PIN
Active Area	152 mm ²	25 mm ²
Capacitance, V _r = 70 V	< 100 pF	< 15 pF
Dark Current @ 25 °C, V _r = 70 V	< 10 nA	< 3 nA
Depletion Voltage	< 70 V	< 70 V
Photo Sensitivity @ λ = 540 nm	> 0.33 A/W	> 0.33 A/W

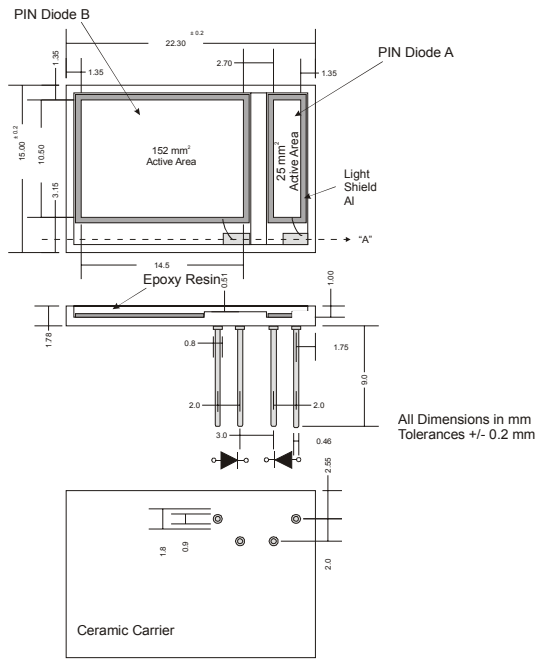


Figure 13. Mechanical Configuration of the GLAST CAL PIN Photodiode Assembly

Based on our experience with the first custom dual PIN diodes, we changed the separation and location of the output pins. We also made a minor change in the height of the ceramic separator between the active areas of the two diodes. This change allows a coating of optical sealant to cover both diodes and generates a flatter diode surface. This flatter surface leads to improved optical bonding to the CsI crystals. In addition, Hamamatsu has developed a technique to polish the optical sealant surface and generate flatter diode surfaces. The technique was successfully demonstrated on a batch of 1999 custom diodes. The delivery of the diodes for the engineering model is expected in August 2001. Figure 13 shows the mechanical configuration of the dual PIN diode.

10.4 CsI Detector Elements

10.4.1 CDE concept

The CsI Crystals are wrapped in reflective material strips (reflective film VM2000 from 3M) that cover the crystal side faces. These reflective strips are attached together and to the crystal by adhesive tape to allow an easy insertion of the assembly into the cell. (See

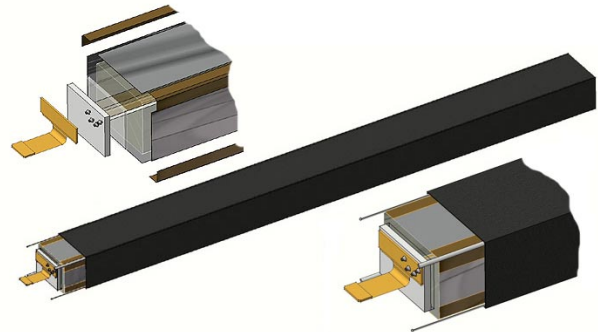


Figure 14. CsI Detector Element expanded view of the end treatment including bonded PIN photodiode and wrapping.

Figure 14, upper left.) The adhesion of this adhesive tape on crystal chamfers is further improved by the rubber band pressure in the PEM cell. The crystal end faces are used for both crystal mechanical stability and light readout.

Readout is performed by Dual Photodiodes (Hamamatsu Photonics) due to dynamic range in the Front End Electronics: each photo-detector is made of 2 PIN diodes, one small (0.25 cm^2) and one large (1.5 cm^2) on the same ceramic carrier. The PIN diode carrier is potted with an hard epoxy and polished by the manufacturer to obtain a flat surface.

The PIN Diode elements (external dimensions $15 \times 22.3 \text{ mm}$) are bonded to the crystal ends by optical adhesive system that has two functions: first the optical contact between the crystal (refractive index 1.8) and the PIN diodes epoxy (index ~ 1.54), and second, mechanical assembly of the PIN diode and the crystal.

The crystal end face free area around the PIN diode is the interface area with the elastomeric bumpers mounted on the Close Out Plate to maintain the crystal position and protect the crystal and accept its dimension change due to thermal expansion.

The CDE design allows tractability, reliability and high light yield performance over the mission life.

10.4.2 CDE Requirements

The CDE must provide a light yield of at least 5000 and 800 e/MeV for the 1.5 cm² and 0.25cm² PIN diodes, respectively, for 3 microseconds Shaping time (TBR).

The light attenuation is 60 % from end to end.

The light attenuation is monotonic over the log length.

The ratio of light yield between large and small diode is 6 (TBR)

10.4.3 PIN Photodiode Bonding

The bonding of the PIN diode to the crystal is made by an optical cryogenic adhesive that can stand the differential dilation of the photo-detector and the CsI(Tl) crystal on the temperature range from -30° C to 50°C determined by environmental constraints.

The requirement is that the bonding can stand the number of thermal vacuum cycles requested by the mission profile (TBR), without diode detachment or light yield decrease by more than 15% (TBR).

Hard epoxies (with high Young Modulus) have been rejected by tests and calculations. Only soft bonding materials can fit. Two gluing systems have been selected according to their low out-gassing properties. Preliminary tests made with CsI crystals and glass (with the diode dimensions) show that, for glue thickness of 0.5 to 1 mm, the adhesion of soft epoxy from Masterbond (~2 Mpa) and Silicon encapsulant (~0.5 Mpa with primer) allow the mechanical bonding and stand the thermal vacuum tests without any degradation,. The bonding specification (bonding system, thickness) is still TBD and will be finalized after extensive thermal cycling of samples made of the final size PIN diodes and CsI crystals.

10.4.4 Bonding process control.

The bonding process is being developed such as to guaranty a bubble free bonding. In addition

during the instrument fabrication phase any drifts in the process will be tracked using dedicated samples that will be bonded using the standard tooling and procedures. These samples are then optically controlled and tested.

10.4.5 Wrapping

Extensive tests on wrapping materials (Aluminum, Aluminized Mylar, silvered Mylar, Tyvek, Tetrak, Millipore filter) have been made and lead to the conclusion that the Visible Mirror 2000 film (VM2000) from 3M has outstanding properties that provide the highest light yield. This film is very thin (65 micrometers) and is stable under environmental constraints.

Out-gassing tests were performed on samples of VM2000 standard products cut in the VM2000 roll. The VM2000 passed the out-gassing CNES specification PSS-01-702, regardless of being out-gassed or not before.

Acceptance tests will be performed on reception to insure the VM2000 reflective properties fit the outstanding optical specifications given by the provider in the wavelength range of interest, between 400 and 700 nm.

The wrapping of the CsI log is then made using VM2000 strips on the crystal faces, attached together and on the crystal chamfers by an adhesive tape (space qualified). This wrapping concept, which uses dedicated tooling, allows an easy insertion of the CDE into the cell structure.

The light yield obtained with such thin wrapping is demonstrated to be as high as the one obtained with thick Tetrak multilayer wrapping enveloped in an aluminum sheet. So it is expected that the CDE meets the light yield requirement of 5000 e/MeV.

10.4.6 CDE Testing

Three vacuum thermal cycles (TBR) will be made on each CDE and comparison of light yield before and after the cycling will insure the

CDE is able to stand the thermal excursion to -30°C (TBC).

The light yield measurement is a check of overall performances of each CDE before insertion into the cell structure, including the

light attenuation specifications. It allows the rejection of a CDE that could suffer from any defect before the insertion into the Calorimeter structure.

10.5 Electronics Design

10.5.1 Electronics Concept

The calorimeter electronics consists of four electronics boards, called the analog front end electronics (AFEE), that are mounted on the sides of the PEM between the Al cell closeout and the outer EMI shield. (See Figure 2.) As shown in Figure 15, the four AFEE communicate with the Tower Electronics Module (TEM) that is mounted, along with the CAL power supply, underneath the PEM baseplate. The CAL controller which is part of the TEM merges the data from the four AFEE cards into a CAL event packet which is combined with Tracker and Trigger system data for transmission to the Trigger and Data Flow system for analysis.

10.5.2 AFEE

Each of the AFEE-boards serves one side of 48 crystals, organized in 4-layers of 12-crystals. Figure 16 shows one of the four 48-channel AFEE boards. It is organized in 4 layers of 12 signal channels with each layer controlled by a layer GLAST Calorimeter Readout Controller (GCRC). A GCRC controls 12 GLAST Calorimeter Front-End (GCFE) ASIC's. A calibration DAC common to all channels on the AFEE-board is also shown in Figure 16. The output of each of the front end ASICs is digitized by a commercial, off-the-shelf (COTS) successive approximation ADC. Thus, the board contains a total of 48 GCFE's, 4 GCRC's, 48 COTS ADC's and 1 COTS DAC (plus connectors, capacitors, and resistors).

In Figure 17 one of the layers with its GCRC is shown in more detail. Each of the 12 GCFE's is communicating with the GCRC. The analog signal from the GCFE is digitized by an ADC and read out to the GCRC. Only the GCRC is communicating with the TEM.

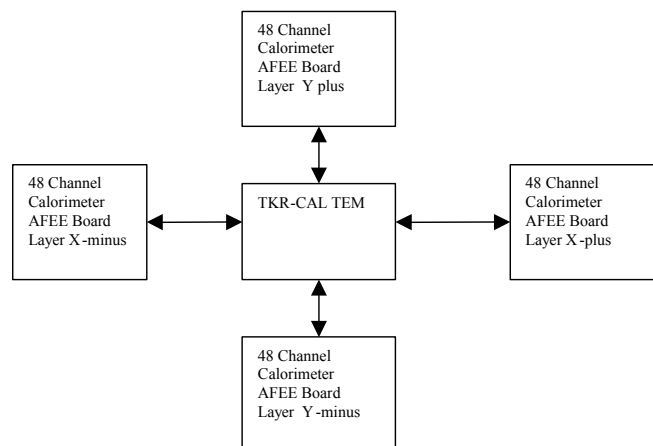


Figure 15. CAL Electronics interface with the Tower Electronics Module (TEM)

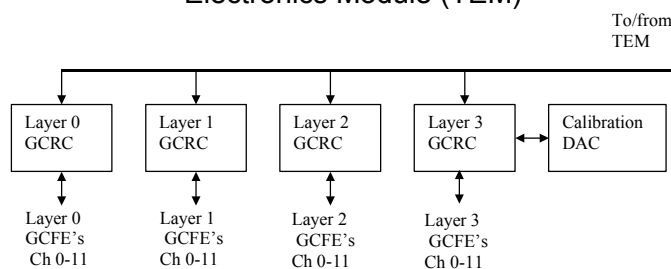


Figure 16. Organization of the AFEE board

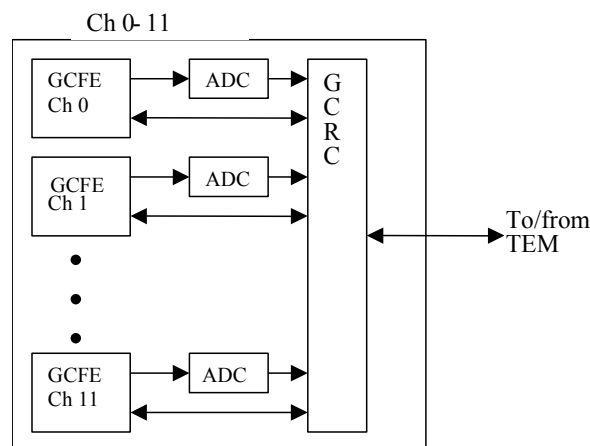


Figure 17. Details of one AFEE layer.

10.5.3 Front End ASIC (GCFE)

The GLAST CAL Front End (GCFE) ASIC amplifies signals from 2 diodes per crystal end, a large area diode covering low energy range, and a small area diode covering the high-energy range. The large area diode is six times the size of the small area diode.

The signals from the two diodes are converted into voltages by charge-sensitive preamplifiers as shown in Figure 18. The gain of the preamplifiers can be adjusted digitally using feedback capacitance switching. The gain can be adjusted by $\sim \times 3$ in 8 steps. A test gain is also provided for the high-energy channel. The output signal of the preamplifiers are split into two paths each: a 0.5- μ sec (fast) and a 3.5- μ s (= slow peaking time) shaping amplifier with a gain of 1.

The 0.5- μ sec shapers are called Fast Low-Energy (FLE) and Fast High-Energy (FHE) shapers. Those shaper outputs are compared to analog (trigger) thresholds by discriminators and transmitted to the digital readout chip. These discriminators are used in the formation of the CAL trigger primitives and are identified as FLE_LLD and FHE_LLD for Fast Low/High Energy Low-Level-Discriminators. The FLE_LLD and FHE_LLD threshold voltages V_FHE_LLD and V_FLE_LLD are generated on-chip by two 7-bit DACs, FHE/FLE_DAC.

The 3.5- μ sec shapers are called Slow Low-Energy (SLE) and Slow High-Energy (SHE) shapers. The output of the the SHE shaper is split into two Track and Hold (T&H) stages, a times one (HEX1) and a times eight (HEX8). The output of the the SLE shaper is similarly split into two Track and Hold (T&H) stages, a times one (LEX1) and a times eight (LEX8). These T&H stages will enable the sampling of the shaper output via a HOLD signal. In normal mode the outputs will be sampled around the time of the peak. The times eight T&H stages (HEX8, LEX8) incorporate a switched capacitor stage with capacitor ratio of 8 to achieve the factor of 8 amplification. Thus, the ASIC

provides energy measurements from a crystal end in four gain ranges. Including the ratio of the diodes, the resulting effective electronic gain ranges are $\times 1$, $\times 8$, $\times 64$, and $\times 512$. This provides the required dynamic range and ADC quantization error.

The outputs of the T&H circuits are connected to a set of discriminators and to an analog multiplexer block. The discriminators and control circuitry function as an auto ranging system that identifies the best of the four ranges to be digitized. The range-selection block determines which of the four T&H output signals to pick and sets the analog multiplexer to output the selected range. In the auto-range mode the highest gain range that is not saturated is selected. Command control of the range and automatic range sequencing modes are also available. The analog multiplexer is followed by an output buffer which adjusts the offset and gain to match the input range of an external ADC.

A discriminator connected to the LEX8 Track&Hold generates a log-accept signal. The latched output, LOG_ACPT, of the discriminator is transmitted to the GCRC ASIC and is later used in data compression logic or zero suppression. This threshold voltage, V_LOG_ACPT, is generated on-chip via a 7-bit DAC, LOG_ACPT_DAC.

There are two control blocks shown in Figure 18. The configuration control decodes external input signals and controls the writing or read-back of on-chip registers and DAC's. The input signals are command (CMD) carrying the GLAST serial command protocol, data-acquisition clock (DAQ_CLK), and reset signal (RESET). When reading back configuration data, the configuration control will take control of the digital output of the IC while sending out the requested data. At other times the digital output line is used by the data-acquisition control block.

The data-acquisition control decodes the RESET and DAQ_CLK signals together with a start-acquisition (START_ACQ) signal. The

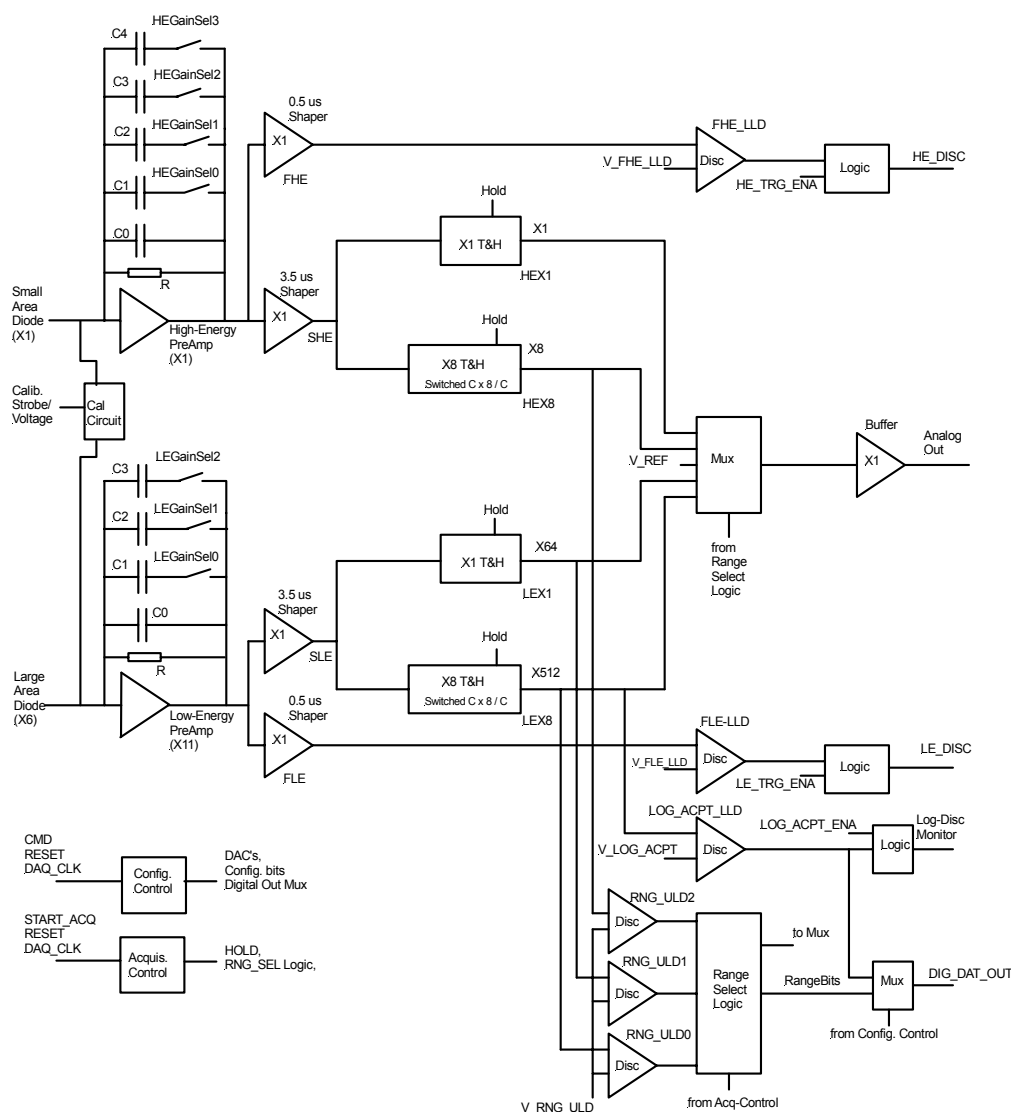


Figure 18. GCFC Block Diagram

circuit controls the T&H, the range-select latches, the range-selection circuit, and the transfer of the range and log-accept bits to the digital output.

The calibration block shown in Figure 18 is used to inject known signals into the preamplifier inputs to measure the transfer function of the signal channels. An external calibration voltage and strobe is applied for that purpose. The low and high energy channels can be enabled in any combination as determined by bits in the configuration register. There are two gain settings for the calibration signal to ensure performance across the entire input signal range.

The Fast Low and High discriminators from the GCFC chips are wired “or” for each layers such that each GCRC receives one high energy and one low energy discriminator for trigger processing. These are processed in the GCRC and transmitted to the TEM electronics for formulation of the CAL-HI and CAL-LOW trigger primitives.

References 14 and 15 define the GCFC ASIC.

10.5.4 Readout Control ASIC (GCRC)

The GLAST CAL Readout Control (GCRC) ASIC is the interface between the log-end GCFC ASICs and the TEM. Figure 19 provides

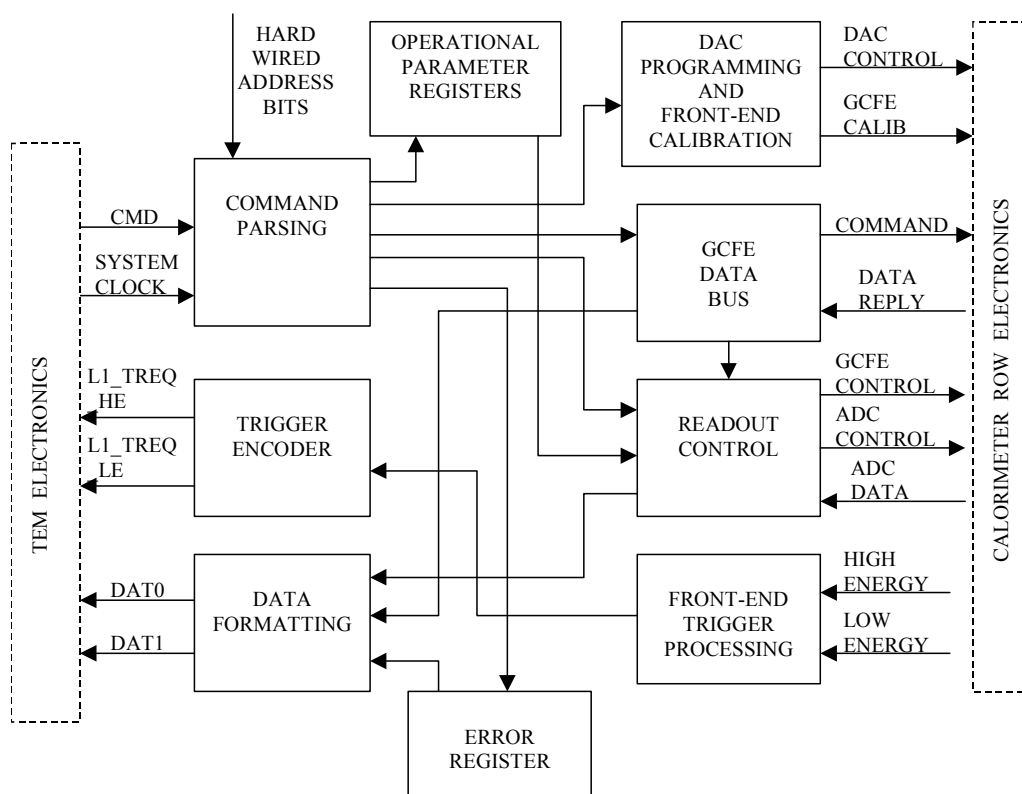


Figure 19. GCRC Block Diagram

a block diagram of the GCRC. The functionality of the GCRC is partitioned such that one GCRC ASIC interfaces one layer, 12 log ends, of the calorimeter. This calorimeter row partitioning follows from using “wired-OR” triggering per calorimeter row and calorimeter printed circuit board constraints of more horizontal routing space than vertical. The GCRCs receive a constant 20 MHz system clock from the TEM, the same clocking frequency of all communication with the TEM.

Figure 18 includes a block for parsing of commands from the TEM. The TEM to GCRC command lines are bussed in parallel to all four GCFC ASICs per side of the calorimeter. The TEM command is one of three types: a) Command Signal Readout (Trigger), b) Command Register Load, or c) Command Register Read. The register load and read commands are used for configuring and verifying the operation of the GCRC.

Upon receiving a Signal Readout (trigger) command, the GCRC immediately executes a

readout cycle by directing the GCFC chips through the signal acquisition cycle, and controlling the digitization by the ADCs.

The nominal readout is digitization of one of the four possible GCFC ranges. Additionally, GCRC can be directed, through the TEM_CMD line to digitize all four GCFC ranges.

Through prior TEM commanding, each GCFC chip is nominally allowed to decide its own optimum range to readout per event. Thus for correct association of the ADC data, the GCRC readout control reads two range definition data bits from each GCFC chip, per range digitized. The range definition bits are passed with the ADC data to the TEM.

Zero suppression, the process of discarding minimal amplitude data, is made easier with a dedicated discriminator bit in each GCFC chip. The GCRC reads this bit, termed Log-Accept Bit, from each GCFC chip during the first range readout cycle. This bit is again passed with the

ADC data, enabling the TEM to quickly zero suppress data with no computation.

The GCRC transmits its data to the TEM using two 20 MHz serial streams of 91 bits. Transmission to the TEM takes $\sim 4.5 \mu\text{sec}$.

Reference 16 defines the GCRC ASIC.

10.5.5 Grounding and EMI

10.5.6 Development Status

The concepts used in the AFEE design are based on those used and tested in the BTEM calorimeter. However, the overall architecture has been modified to be consistent with LAT-wide communications protocols and data organization. As a result, the ASIC developments for the AFEE are totally new designs for CAL but are based on previous designs used at SLAC on the BaBar experiment. There is also significant leveraging of designs used in the LAT Tracker subsystem.

Two revisions of the GCFE ASIC have been submitted for development fabrication runs. The second submission has not returned. Testing on the first submission has proven fully functional digital control sections but exhibits a problem with the preamplifier section that is still being investigated.

The GCRC ASIC concept is currently in review. The design will be created in VHDL and tested in FPGAs. Synthesis and submission of the first version of the ASIC will occur in XXX???

GCFE test boards have been fabricated for demonstrating functionality, noise performance, linearity and interface characteristics with the COTS ADC.

Table 8. CAL Temperature Ranges

State	Temperature Range (°C)
Operational	– 10 to +25
Storage / Survival	– 20 to +40
Qualification	– 30 to +50

10.6 Thermal Design

The bolted joint interface between the LAT GRID and each CAL module is the primary mechanism for transferring heat into and out of the CAL module. Heat generated by the TEM and Power Supply mounted on the CAL baseplate is also transferred to the GRID via this bolted joint.

The LAT thermal control system is designed to keep the top surface of the GRID (the Tracker interface) at 0 deg C. Thermal gradients in the GRID are expected to produce temperatures at the CAL baseplate bolted joint in the range of 0 – 5 deg C.

Table 8 summarizes the design temperatures for the CAL subsystem. Additionally, CAL temperature rate of change must be limited to 5 degrees per hour.

10.7 Mass and Power

Table 9 summarizes the current mass estimate for a single calorimeter module. The current estimate, 92.195 kg, uses “average” CsI crystal sizes; that is, crystals that are centered in the dimensional tolerance interval. In actuality, we expect the crystals to tend to the maximum permissible size which would add ~ 1.5 kg per module. However, we have weighed the first 24 crystals shipped by Amcrys H and they do tend to the maximum dimension but have average mass of 790 gm (see Reference 50). That CsI mass leads to a module total of 89.3 kg.

This module mass includes a 6 mm solid plate addition to the previous baseplate design, providing an effective stiffness of a 12 mm solid Al plate. This compares to a stiffness requirement in the CAL-LAT ICD of equivalent to 8 mm plate.

Table 10 summarizes the current power estimate for a single calorimeter module. The estimate is ~ 1.8 Watts per module below the allocation for a total margin of almost 30 Watts.

Table 9. Current Mass Estimate for a CAL Module

Component	Material	Quantity per Module	Mass in Kg per Module
Composite Structure			3.363
GFRP structure	Graphite epoxy core	1	3.140
Side insert	Ti-6Al-4V Titanium	40	0.075
Top insert	Ti-6Al-4V Titanium	16	0.045
Bottom insert	Ti-6Al-4V Titanium	25	0.103
Structure shell			7.090
Top frame	2618A Aluminum alloy	1	0.750
Bottom plate	2618A Aluminum alloy	1	4.450
Close-out plate	2618A Aluminum alloy	4	0.945
Corner	2618A Aluminum alloy	4	0.250
Spacer	2618A Aluminum alloy	10	0.055
Side panel	5754 Aluminum alloy	4	0.640
Dampers			0.320
Damper elastomer	RTV Silicone	192	0.090
Damper frame	2618A Aluminum alloy	192	0.100
Elastomeric cord	Silicone	384	0.130
Fasteners			0.500
Total batch	A 286		0.500
Total Mass of mechanical structure			11.273

Component	Material	Quantity per Module	Mass in Kg per Module
Crystal Detector Element			79.132
CsI Crystal	CsI	96	78.703
PIN Photodiode	Ceramic, Epoxy	192	0.332
Kapton Cable	Kapton, Copper	192	0.019
Epoxy Optical Bond (1 mm thick)	Epoxy	192	0.077
Printed Circuit Boards(AFEE)			1.690
PCB with parts	Polyamide	4	1.440
TEM Cables	Kapton, Copper	8	0.250
Miscellaneous			0.100
Total Mass of CAL Module (kg)			92.195
CAL Allocation Per Module (kg)			93.250

Table 10. Current Power Estimate for a CAL Module

Item	Quantity	Power (mW)	
		Each	Total
GCFE	48	8	384
ADC Max145 (no sleep)	48	4	192
Digital Controller ASIC	4	80	320
DAC	1	6	6
DAC Buffers	4	5	20
References	2	5	10
LV Biasing	48	1	24
PIN Bias	1	1	1
TOTAL Power per AFEE (mW)			957
TOTAL Power per Module (mW)			3,828
Allocated Power per Module (mW)			5,688

11 ASSEMBLY & TEST

11.1 CDE Assembly and Test

Storage and handling of CsI logs

Long term storage of the logs shall be made at $20 \pm 2^\circ\text{C}$ and a maximum humidity: level of 10% (inside sealed polyethylene bags or in a dry storage area of a clean room).

During tests, bonding of photodiodes, temperature shall remain controlled at $20 \pm 2^\circ\text{C}$ and humidity shall stay below 50%.

The logs shall be removed from their sealed bags only inside a clean room, at least ISO7 class.

The crystals shall always be stored inside V-blocks. The flatness of the contact surface shall be less than 0.05mm.

When handled, the crystals shall remain inside the support blocks.

When handling the crystals, clean latex gloves are required even if the crystals are wrapped.

11.2 PEM Assembly and Test

Table 11 shows the test matrix that summarizes the environment tests achieved on the different PEM models. The tests levels shall be based on the NASA standard GEVS-SE.

Performance tests shall be performed at ambient temperature before, between and after each environmental test phase. A cosmic muon test bench will be used for performance tests.

The following performance characteristics shall be measured :

- Single crystal light yield obtained for the large and small diodes
- Tapering characteristics calculated with the light yields of the 2 dual-diodes of each single crystal, for large and small diodes
- Hodoscopic performances
 - Position
 - Angle

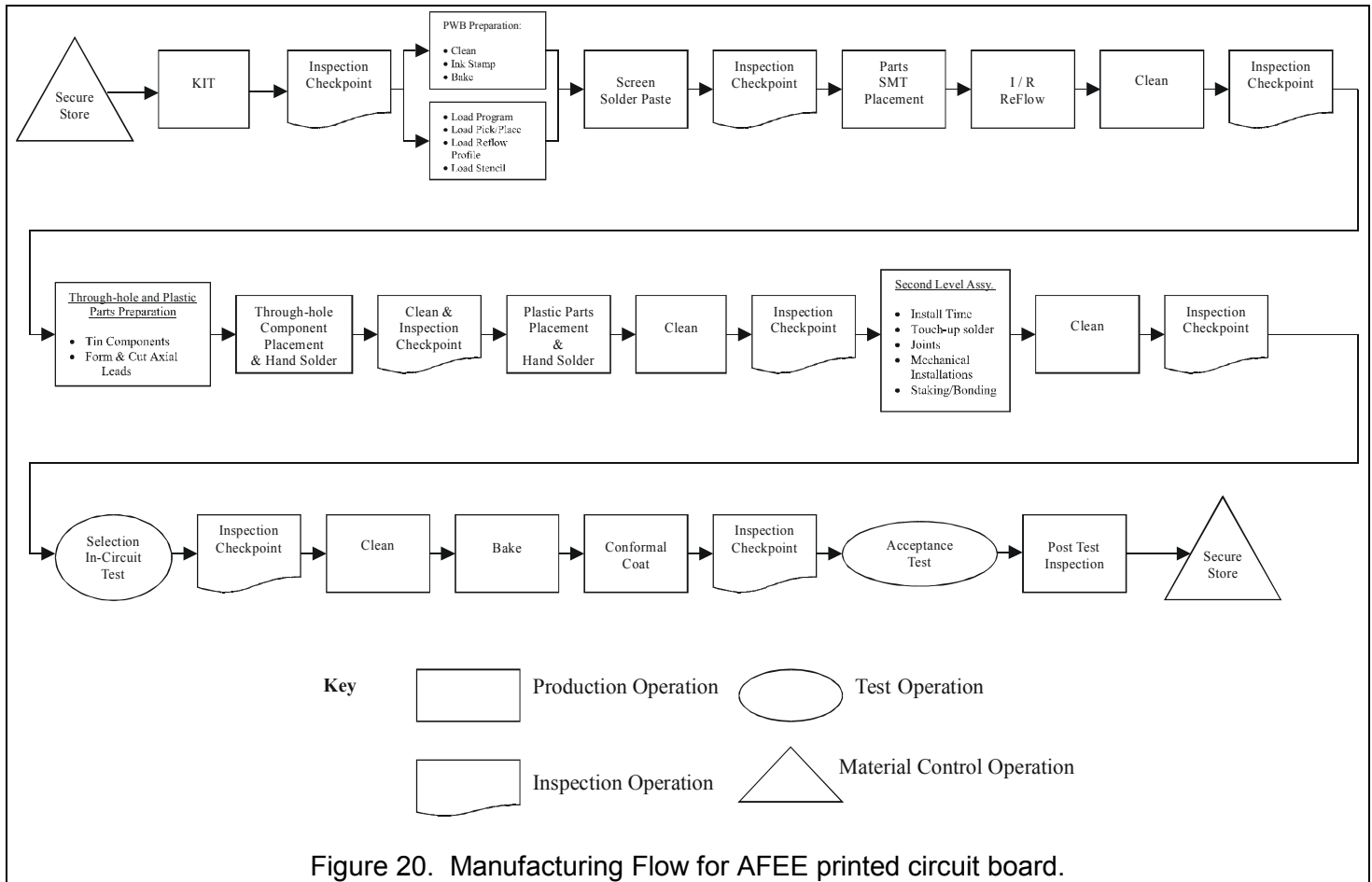
thermal-vacuum tests on EM, QM, FM and FSM PEM are to be confirmed because these tests will be achieved on entire CAL modules.

Achievement of environmental mechanical and

Table 11. Verification Matrix for PEM Assemblies in France

ENVIRONMENTAL TESTS		VM2	EM-PEM	QM-PEM	FM-PEM	FSM-PEM
STRUCTURAL & MECHANICAL	MODAL SURVEY	M	M	M	M	M
	STATIC LOADS	M	M(TB C)			
	ACCELERATION					
	SINE BURST	Q	Q	Q	A	A
	SINE VIBRATION (TBC)	Q	Q	Q	A	A
	RANDOM VIBRATION	Q	Q	Q	A	A
	ACOUSTICS					
	MECHANICAL SHOCK					
	PRESSURE PROFILE	Q	Q	Q	A	A
	TORQUE RATIO					
	LIFE TESTS					
	MASS PROPERTIES	M	M	M	M	M
THERMAL	LEAK					
	THERMAL-VACUUM CYCLES NUMBER OF CYCLES (TBC)	Q 8	Q 4	Q 2	A 1	A 1
	THERMAL CYCLES (NON VACUUM)					
	THERMAL BALANCE	M				
	TEMPERATURE-HUMIDITY					
	BAKEOUT					
	PERFORMANCES TEST @ AMBIANT TEMPERATURE	M	M	M	M	M
	PERFORMANCE TEST @ TEMPERATURE LIMITS					
EMC						
ELECTRICAL	INSULATION RESISTANCE	T	T	T	T	T
	CONTINUITY	T	T	T	T	T

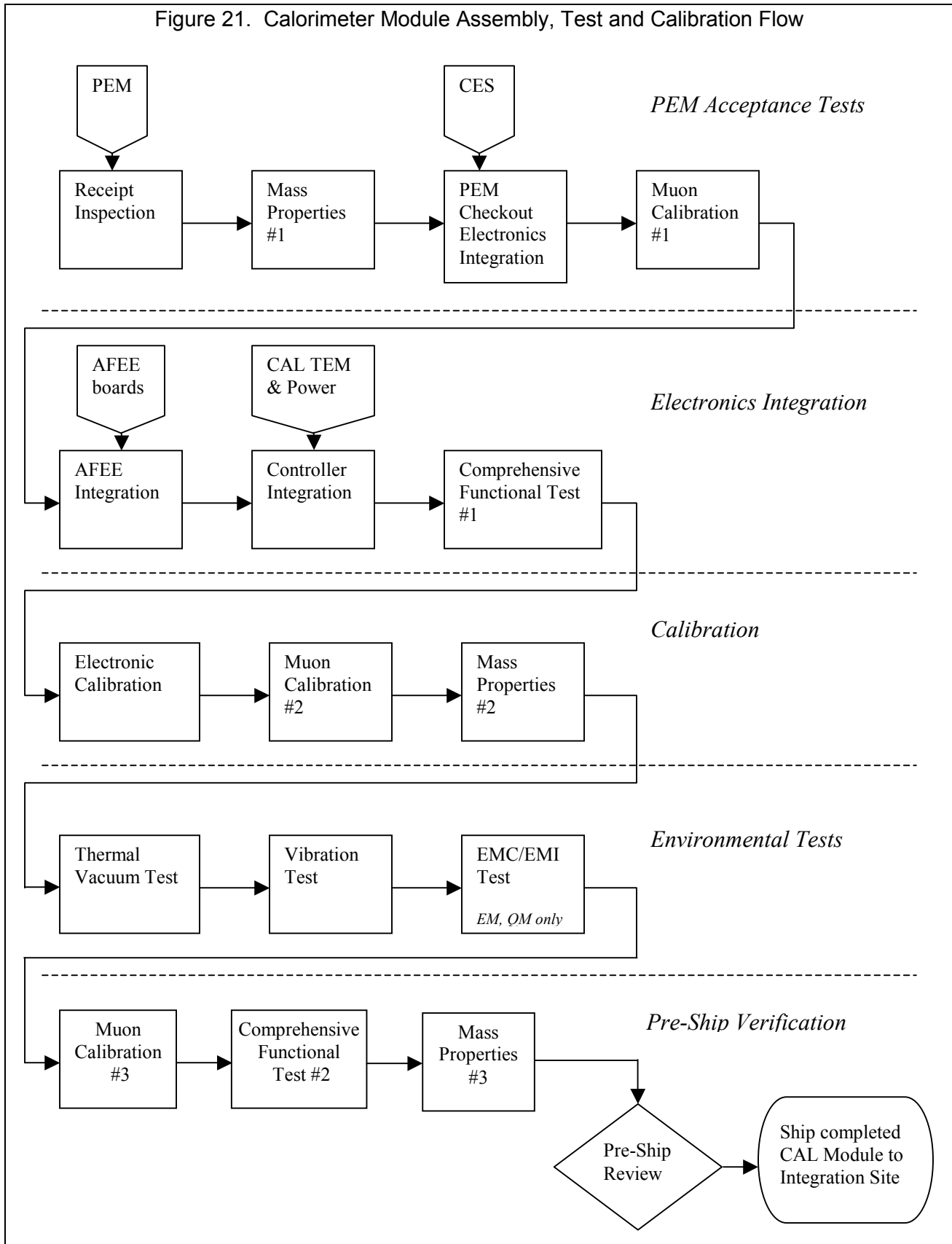
N.A.: non achieved T=Test M=Measure Q=Qualification level test A=Acceptance level test



11.3 Electronics Assembly and Test

Figure 20 shows the manufacturing flow for the AFEE printed circuit boards. The ASICs are encapsulated in plastic carriers and are, along with the COTS ADCs, manually soldered to the boards.

Figure 21. Calorimeter Module Assembly, Test and Calibration Flow



11.4 CAL Module Assembly, Test, and Calibration Sequence

The following assembly and test sequence applies to each of the 19 CAL Modules. A flow chart of this sequence is shown in Figure 21, where it is divided into five general themes: (A) acceptance tests of the PEMs, (B) electronics integration and checkout, (C) calibration, (D) environmental tests, and (E) final verification and preparation for shipping.

We note that this sequence includes acceptance tests for the PEMs, but it assumes that elements to be integrated with the PEMs – the AFEE boards, calorimeter TEMs, and flight power supplies (TBR) – are accepted and verified separately, prior to entry into this sequence. We expect to integrate flight TEMs and deliver them to the Instrument Integration site as part of the CAL. (See Figure 22).

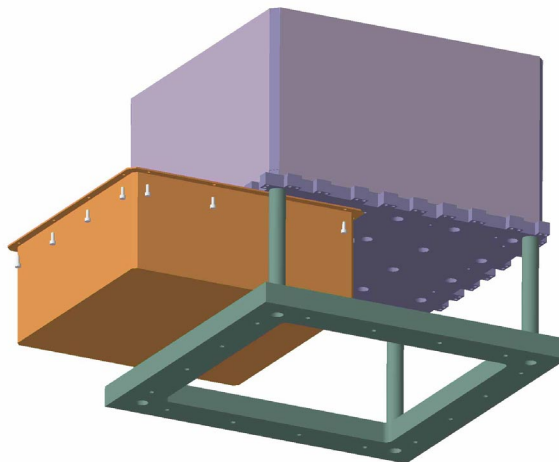


Figure 22. CAL Module on MGSE stand. TEM and Power Supply are being installed on bottom of Module baseplate.

7. Comprehensive State Functional Testing #1. Establishes full functionality of integrated CAL Module. Analyze and document results.

Calibration

8. Electronic Calibration. Charge injection calibration. Analyze and document results.
9. Muon Calibration #2. Establishes baseline gain of integrated system. Analyze data. Compare with PEM-CES response and known gain of AFEE. Document results.
10. Mass Properties Measurement #2. Establishes weight, center-of-mass, and physical dimensions of assembled CAL Module.

Environmental Tests

11. Thermal-Vac Testing. Four cycles over qualification or workmanship range (as appropriate for the module under test), with temporal gradient $<10^{\circ}\text{C}$ per hour and holding temperature limits at least 2 hours. The plateau time shall be based on the time required to perform performance/functional tests, but shall not be less than 2 hours. Require operation and functional tests during only one cycle at the hot and cold

PEM Acceptance Tests

1. Receipt at NRL. Comparison with shipping logs to confirm identity of items shipped. Visual inspection for shipping damage.
2. Mass Properties Measurement #1. Establishes weight and physical dimensions of PEM.
3. PEM Checkout Electronics Integration. Install PEM in PEM-CES for readout of large and small PIN diodes of each log face. Limited functional test of EGSE hardware.
4. Muon Calibration #1. Confirms quality of PIN diode bonds and generates light attenuation maps. Minimum run time = 24 hrs. Document results.

Electronics Integration

5. AFEE Integration. Attachment of CAL AFEE boards and 192 flex cables. Inspection.
6. CAL TEM Integration. Integration and simple aliveness test. Document results.

plateau. Limited performance test following each cycle. Document results.

12. Vibration Testing. The vibration testing comprises three components: modal frequency verification, sine burst testing, and random vibration testing. Includes limited performance test. Document results.
13. Electromagnetic Compatibility Testing. Establishes electromagnetic noise production and susceptibility. Test is performed only on EM and QM models. Document results.

Pre-Ship Verification

14. Muon Calibration #3. Establishes no degradation in performance during environmental testing and handling.
15. Comprehensive Performance Testing #2. Establishes no degradation in operation during environmental testing and handling.
16. Mass Properties Measurement #3. Establishes no deformations during environmental testing and handling.
17. Pre-ship Review and Sign-off. Establishes readiness for shipment.
18. Shipment to LAT Instrument Integration Site.

Further details of the assembly and test sequence are given in the following subsections. The durations of the activities are given for the individual PEMs or Modules in LAT-SS-000262. Generally, we have allowed more time for each activity for the earlier PEMs, under the assumption that with practice the procedures will move more quickly and efficiently.

11.4.1 PEM Acceptance Tests

The PEMs are delivered to NRL following their assembly and verification in France. A number of acceptance tests will be performed at NRL to

determine compliance with specifications prior to any assembly of the Modules.

The calorimeter PEMs will be received at NRL's A&T Cleanroom. The components will be removed from their shipping containers and inspected by NRL Quality Assurance personnel for item identification against the Cert log and other shipping papers. A visual inspection will be made to ascertain the condition of the hardware and to note any visual abnormalities. Receipt status and comments will be entered into the CAL Module Properties Database.

Each PEM will be weighed and its physical dimensions will be measured. A Technician will confirm that the measured mass and dimensions comply with the relevant requirements. Measurements and compliance will be entered into the CAL Module Properties Database.

To measure the absolute scintillation light yield and generate light attenuation maps in each CsI(Tl) crystal, a detailed muon calibration will be performed on each PEM. In turn, each PEM will be integrated with the PEM Checkout Electronics System (PEM-CES), which provides simultaneous, 192-channel readout of PIN photodiodes, along with additional channels for the Muon Telescope (Section 11.6). The muon telescope is comprised of two multi-wire proportional counters, each 50 cm × 50 cm in area and measuring positions in two dimensions to better than 3 mm (rms). The telescope triggers when a cosmic-ray muon passes in coincidence between the wire chambers. The CES data acquisition system will log PEM and muon telescope data from a muon run of at least 24 hours duration. GSE software will accumulate the CsI scintillation signal in each log as a function of position deduced from the muon trajectory derived from the wire chamber positions, and generate maps of CsI response for each log. A technician will confirm that the light yield and light attenuation maps are consistent with those generated prior to shipment from France. Measurements and

compliance will be entered into the CAL Module Properties Database.

A PEM that has suffered no visible damage and complies with the specifications on mass, size, light yield, and light attenuation shall be deemed to have passed acceptance tests. Acceptance specifications are given in Calorimeter Acceptance Standards and Tests (LAT-TBR).

11.4.2 Electronics Integration

Following successful acceptance, each PEM will be integrated with its four front-end electronics boards (AFEE). The boards are assembled and tested prior to integration with PEM.

The four AFEE boards will be mechanically attached, and the 192 Kapton flex cables attached to the Front End boards. As each board is integrated, Kapton attachments will be inspected by a QA technician, and a simple power-up aliveness test will be performed using laboratory power supplies and TEM simulator. During integration of PEMs EM, A, B, 1, and 2, aliveness and simple functional testing and inspection will be performed after each of the AFEE boards is attached. For later PEMs, this testing will occur only after all four boards are integrated.

The integrated PEM and AFEE form a completed CAL Module.

The CAL Module will be integrated with its flight Tower Electronics Module (TEM) and flight power supply (TBR). A power-up and aliveness functional test will be performed on the integrated Module and TEM.

The CAL Module and TEM will be subjected to comprehensive performance and functional testing to confirm compliance with operating and performance requirements as an integrated whole. Comprehensive Performance Tests (CPT) are detailed functional tests conducted under conditions of varying internal and external parameters with emphasis on all possible modes of operation for the Module and TEM. Functionality will be compared with

AFEE checkout to confirm no loss of performance.

11.4.3 Calibration

Following integration with the AFEE and TEM, each CAL Module will require calibration of both the electronic gain of the front end and the optical gain of the CsI – PIN diode coupling. These electronic and optical gain calibrations can then be compared to the corresponding gain calibrations performed on the AFEE and PEM sub-elements prior to integration.

The CAL Module and TEM will be calibrated following the Electronic Calibration Procedure (LAT-TBD), which was extensively prototyped with the Beam Test and Balloon Flight Prototype Calorimeters. This is a charge-injection calibration of each of the 384 analog and digital electronics channels. Charge is injected into each analog front end at a repetition rate of 100 Hz covering the full dynamic range of the electronics. The primary output of this test is a set of 384 electronic gain calibration curves. Test results and performance summary will be logged to the CAL Module Properties Database.

The Module and TEM will be reintegrated with the muon telescope, and a second long muon data set will be accumulated. Following the run, the data will be analyzed by Module EGSE software to derive scintillation light yields and light tapering response maps. The relative light yields and light-tapering functions from the muon calibration will be compared to PEM-CES response and the known gain of the FEE to confirm expected change in instrument performance. This calibration establishes the baseline gain of the integrated system. Results of this run and comparison will be logged in the CAL Module Properties Database.

Finally, the completed CAL Module will be weighed, its center of mass determined, and its physical dimensions will be measured. A Technician will confirm that the measured mass and dimensions comply with the relevant

requirements. Measurements and compliance will be entered into the CAL Module Properties Database.

11.4.4 Environmental Tests

Following calibration, each CAL Module and TEM will be subjected to environmental testing in thermal-vacuum, vibration, and – for the EM and QM Modules – electromagnetic compatibility tests.

The CAL Module and TEM will be subjected to four thermal-vacuum cycles over a wide temperature range with a temperature gradient of <10C per hour. The plateau time will be based on the time required to perform Limited Performance Testing but will not be less than two hours. The temperature range shall cover a broader range for the EM, A, and B Modules, and a narrower workmanship range for Modules 1–16. The temperature and pressure ranges and the duration of the test will comply with the requirements specified in LAT-TBD. The Module will be powered during one of these thermal-vac cycles: Limited Performance Tests (LPTs) will be performed at the hot and cold temperature plateau. Measured temperature profiles and test results will be logged in the CAL Module Properties Database. LPTs will be performed at the completion of the cycling to ensure no degradation in operation.

Special consideration must be given to prevent hydration and/or condensation during all setup and test operations. All cold cycles will be performed in a dry environment. Sufficient time to ensure return to ambient temperature for all portions of the Module must be allowed. To prevent water condensation, a cold Module must not be exposed to ambient air.

Each CAL Module will be subjected to vibration testing to verify its compliance with its mechanical design parameters and to demonstrate its robustness against the launch vibration environment. The vibration testing shall comprise three subsets: minimum modal frequency verification, sine-burst strength

testing, and random vibration testing. Test vibration levels and requirements are given in LAT-TBD. Measured resonance and vibration profiles and test results will be logged in the CAL Module Properties Database. LPTs will be performed at the completion of vibration testing to establish no degradation of performance.

The Engineering Model and Qualification Model (Modules EM and A) will be subjected to electromagnetic compatibility (EMC) testing to ensure that it will neither be a source of electromagnetic interference (EMI) nor be susceptible to EMI when integrated with other components of the LAT. EMC/EMI testing of the 16 flight CAL Modules and the flight spare is not required: verification of compliance with EMC/EMI requirements will be by assessment of similarity with the QM. LPT will be performed at the completion of EMC/EMI testing.

11.4.5 Pre-Ship Verification

Following environmental testing, a series of functional and scientific performance tests will be run to ensure that each Module is ready for shipment to the LAT Instrument Integration Site. A satisfactory pre-ship review is required.

A third and final long-duration muon run will be performed. The data will be analyzed by Module EGSE software to derive scintillation light yields and light tapering response maps. The relative light yields and light-tapering functions from the muon calibration will be compared to the pre-thermal-vac and pre-vibration response to confirm no change in instrument performance. Results of this run and comparison will be logged in the CAL Module Properties Database.

A second and final series of CPTs will be run to confirm no degradation of operation or performance during environmental testing. This test will repeat the Comprehensive State Performance Testing #1, although some tests will be abbreviated. Test results and

performance summary will be logged to the CAL Module Properties Database.

A third and final mass properties measurement will be performed, primarily to confirm that no deformations to the mechanical structure occurred during environmental testing. Measurements will be compared to those from the second mass properties test, and the summary will be logged to the CAL Module Properties Database.

A Pre-Ship Review will be held. Test Reports and associated resolution reports will be

assembled for presentation to the Pre-Ship Review Board. The status of all discrepancies, functional anomalies, subsystem failure-free operating hours, and out-of-tolerance levels detected during the Assembly and Test process will be presented to the Board. This review will contain all items written against the Module and the associated GSE. The disposition of all reports and actions will be included or attached to a summary report, which will accompany the Module during Instrument I&T.

11.5 Manufacturing and Producibility

Manufacturing and Producibility process development is accomplished using concurrent engineering techniques. Materials' engineering reviews and approves all material and related processes for each application to confirm that they meet design requirements. Process development originates jointly within the engineering and manufacturing engineering disciplines with participation from Quality Assurance, Manufacturing, Safety, and other pertinent organizations as necessary as shown in the figure. Once a process is optimized, qualification and certification is accomplished by the use of process qualification samples produced under controlled conditions to documented procedures by trained manufacturing personnel. These process qualification samples are then reviewed and approved by engineering, quality assurance, manufacturing engineering and any other applicable disciplines prior to process certification. Manufacturing process procedures are likewise then reviewed and approved. These procedures define the materials and equipment required, key process parameters, process control steps, and process corrective actions. Preventive maintenance of all processing is documented, controlled, and performed on established schedules.

Controls are implemented from receipt and continue through receiving inspection, stocking, kitting, kit audit, manufacturing, test, inspection, customer/government acceptance, shipment and delivery. All personnel are trained and certified before being allowed to be in the proximity or in

contact with parts or hardware.

Standard workmanship acceptance criteria, as defined in NASA-STD-8739, are used by trained and certified inspection personnel. Special circumstances are defined through consultation with cognizant engineering to determine measurement techniques and parameters. These special attributes are documented in documented inspection instructions and address inspection characteristics as well as inspection methods and provide or reference inspection criteria.

NRL has facilities in place to manufacture and test the hardware required for this program. We have extremely tight process control during the critical assembly process.

All manufacturing processes address flight hardware and cover items such as traceability, failure reporting and corrective action, part stress derating, soldering and other manufacturing processes.

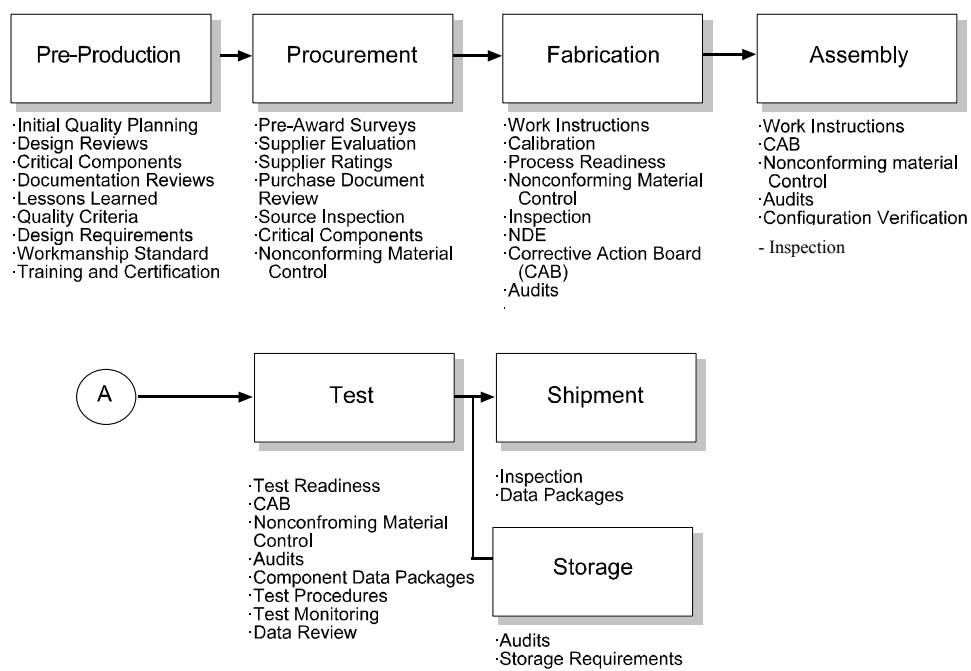


Figure 23. Manufacturing Producibility Process Flow with Process Quality Control

11.6 Ground Support Equipment (GSE)

The ground support equipment (GSE) requirements are derived from the requirements necessary to integrate, test, lift, handle/hold, ship, maintain cleanliness, safe, operate, support integration activities for the Calorimeter subsystems. Section 3.3 includes specifications for GSE items required in the assembly and test of CAL. A summary of the GSE is given below:

11.6.1 Mechanical GSE

Elements of the MGSE include shipping containers, transportation dollies, test fixtures, assembly fixtures and work stands, and lifting fixtures.

Among the more specialized elements are 19 dry storage and shipping containers for the PEMs and assembled Modules, rotation/assembly mounts for the integration of the AFEE boards with the PEMs, and an automated xy translation stage for accelerator beam tests of the EM Module. Prototypes for each of these items were developed and used in the assembly and test of the Beam Test Prototype Calorimeter.

11.6.2 Electrical GSE

Muon telescope: Two muon telescopes capable of providing <3 mm (one sigma) positioning simultaneously in two dimensions in all layers of a CAL Module are required. Each telescope must be sufficiently large to enclose a single CAL Module. We constructed prototype multi-wire proportional counters as a muon telescope for the assembly and test of the Beam Test Prototype Calorimeter. Two wire chambers are required for each telescope. The prototype telescope and the 48-channel data acquisition system is shown in Figure 24. As shown, upper and lower 50 cm \times 50 cm 2D wire chambers surround a test array of 20 CsI crystals.

One telescope is necessary to meet the delivery schedule for CAL Modules. The second telescope is available as a spare or to meet contingencies in the assembly schedule.

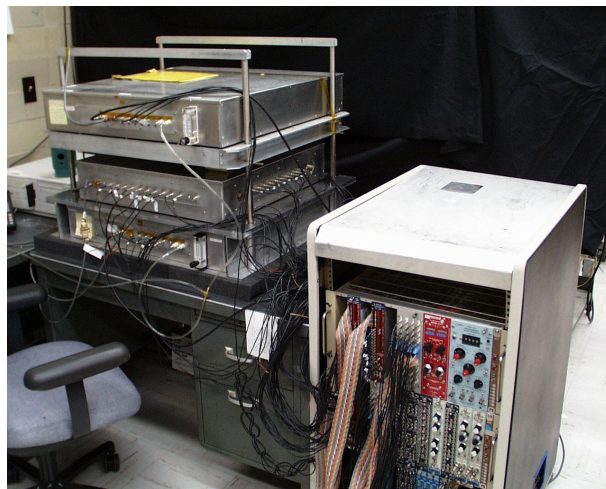


Figure 24: Prototype muon telescope and 48-channel data acquisition system.

PEM Checkout Electronics System: The PEM Checkout Electronics System (CES) provides readout, digitization, acquisition, and analysis of all 384 PIN photodiodes in a PEM. It shall comprise at least 192 channels of low-noise preamplifiers, shaping amplifiers with shaping time compatible with CsI(Tl) scintillation pulses, and analog-to-digital converters. It shall support both self-triggering by the PEM and external triggering. It shall contain sufficient discriminators and logic to allow a trigger on any of the 96 crystals of a PEM.

The PEM CES requires a PC-based data acquisition, archiving, and analysis system. The data acquisition system shall be compatible with either CES or Module Controller data streams.

The crystal test array and data acquisition system shown in Figure 24 is a prototype of the CES.

A&T Computer System: During assembly and test, the PC-based A&T computer system will provide the data capture, acquisition, and decommutation, command generation, telemetry conversion to engineering data, display of engineering data, functional test procedure execution, and network interface to the

subsystem GSE. Multiple PCs are required to support the simultaneous processing of five CAL Modules. Each A&T computer system will be equipped with an uninterruptible power supply (UPS).

General Purpose Lab Test Equipment: This set of equipment is comprised of oscilloscopes, volt/current/impedance meters, milliohm meters, strip chart recorders, spectrum analyzers, optical measuring equipment, and various hand tools.

Breakout Boxes (BOBs): BOBs are required to support the electrical integration of components with other components through the wire harness. The signals of the electrical interfaces are observed, using oscilloscope and meters, before and after electrical mating.

Test Cables: Test cables provide hookup of the EGSE to the Calorimeter subsystem during performance testing, functional testing, and health and safety monitoring. These will include the ability to connect through the vacuum chamber wall and within the EMC test facility.

11.7 Contamination Control

The Calorimeter subsystem will be fully integrated in a class 100,000 cleanroom facility. The following list of materials and supplies are required to support the cleanroom activity:

- Cleanroom garments
- Cleanroom gloves
- Cleanroom wipes
- Cleaning solvents
- Paper and report covers
- Portable vacuum equipment
- Tape-lift supplies measurement
- Molecular contamination sampling supplies
- Witness plates, stainless steel
- Room air particle counter
- Cleanroom bagging material

Details are found in the Calorimeter Contamination Control Plan (LAT-MD-00228).

11.8 Quality Control, Work Order Authorization (WOA) and Material Control

All parts and materials required for manufacture and assembly of Calorimeter subsystem are processed through receiving and inspection department and stockroom. These areas are specially designed for temperature and humidity controls, and ESD to ensure an appropriate storage and handling environment for parts and components. All EEE parts involved in the soldering process receive 100% visual inspection significantly reducing rework at the assembly level and resulting in a higher quality product. Traceability of EEE parts begins in receiving inspection where all purchase order quality assurance provisions, manufacturer and lot information are documented and verified. Traceability of individual parts or components or lots of parts/components is accomplished using pertinent information about each lot of material including flight or non-flight, manufacturer, serial numbers, date codes, lot numbers, or other information.

Any material determined to be non-conforming is segregated for formal review by quality assurance and customer/government personnel as required by contract. Acceptable material packaged and stored in a secured, segregated storage area under controlled temperature and humidity conditions.

Quality assurance sign-off is required for work order release or revision and is responsible to verify that needed inspection points and inspection instructions are provided. These identified points are reflected through work order operation call out and supporting routing text.

The quality assurance program for the flight hardware not only includes the standard inspection support but also includes such activities as operator/inspector training/certification, fabrication data records, alert support, traceability, defect control

documentation records, audits, process controls and many other activities.

Work Order Authorization (WOA) and Material Control

All work will be done on an approved WOA. This work will include, but not limited to, box/component integration, functional testing, troubleshooting, environmental tests, and moving CAL hardware. The WOA will specify the hardware items involved in the task, provide a brief description of the work to be performed, list the required documents, call out any hazards, and provide for the necessary approval signatures. The WOA form allows for short procedure steps to be included as part of the document in lieu of a separate formal procedure document. Attached procedures must be

approved by the I&T Manager, cognizant engineers and QA.

The WOA flow diagram shown in Figure 25 illustrates the process and provides a way to plan the work and keep a record of the work being performed/completed. A separate log will be maintained on a daily basis showing the status of all WOAs by WOA number and title. The WOA forms will be maintained by a QA representative, including the log-in and sign-off of the work as completed. WOAs will be initiated by Subsystem Leads, Systems and the I&T Manager or designated representative. WOAs must be approved by the I&T Manager, or delegated representative, Systems Lead, Systems, QA, and appropriate Subsystem Lead.

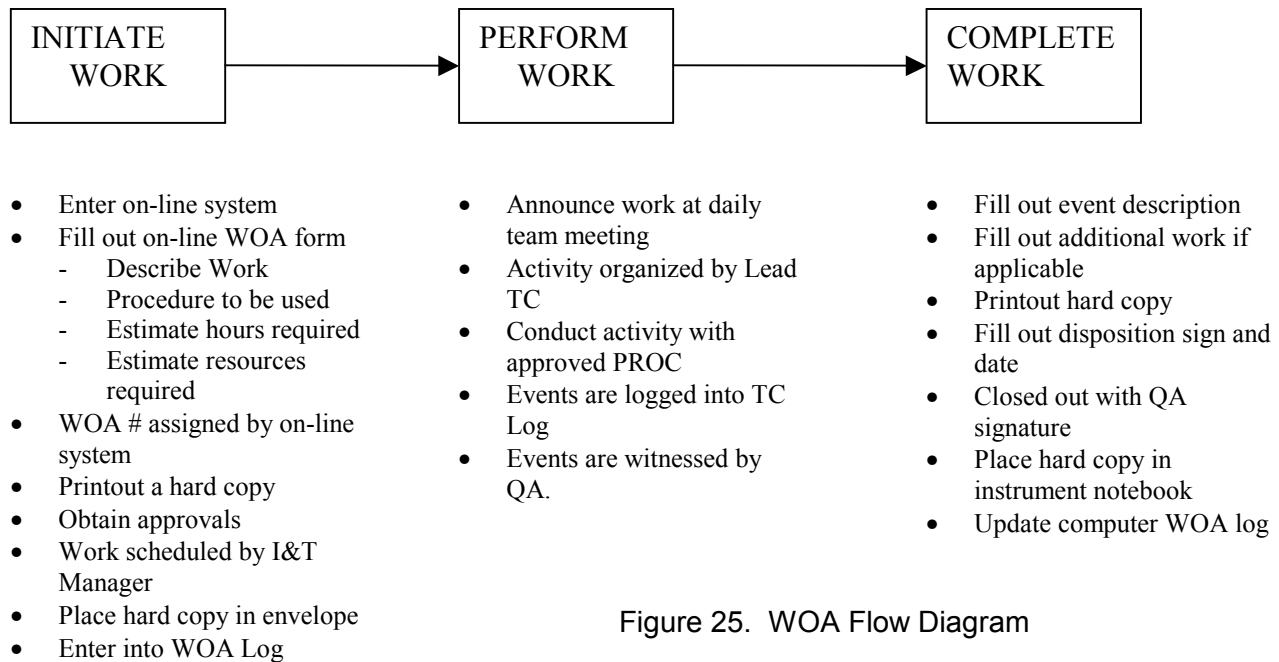


Figure 25. WOA Flow Diagram

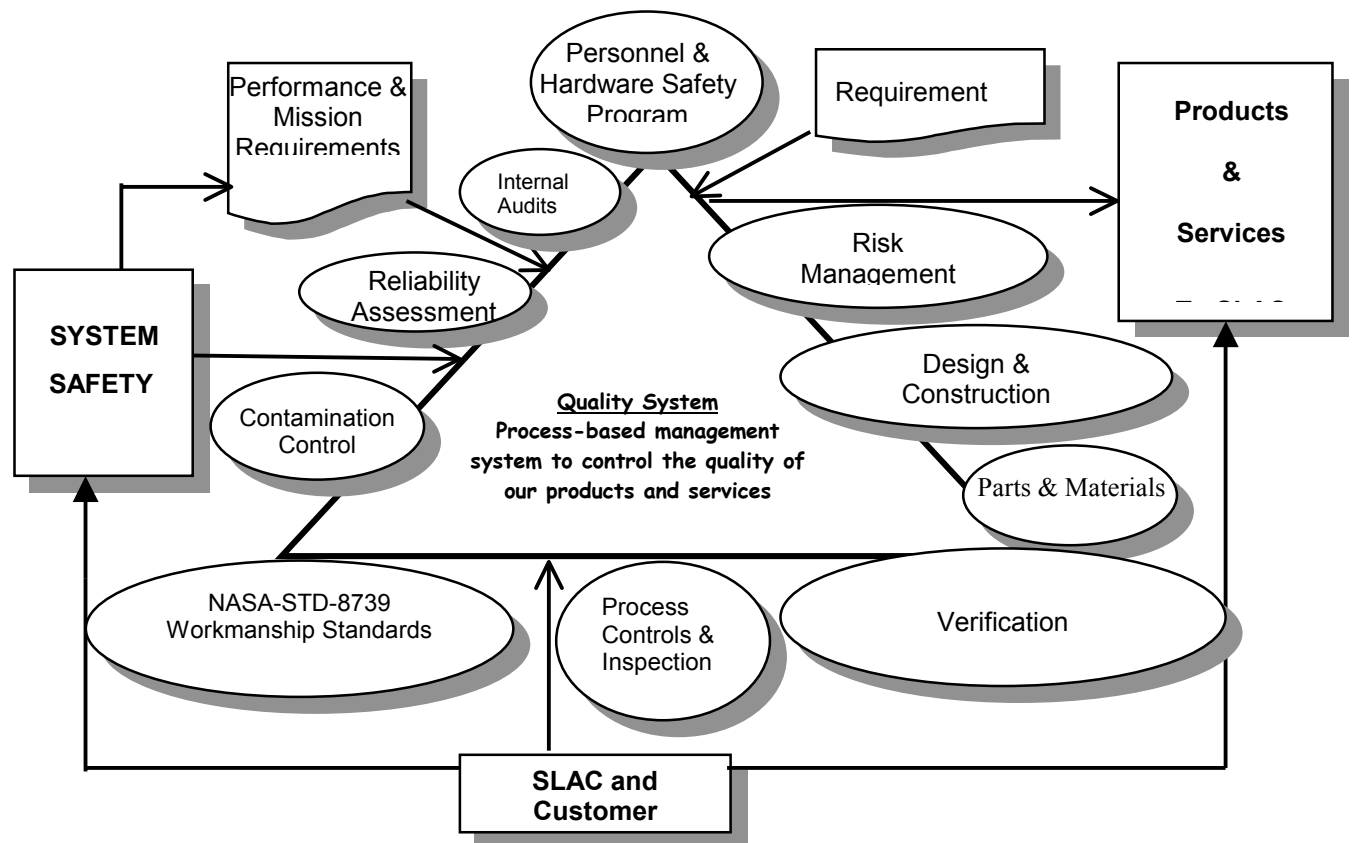


Figure 26. Quality Assurance System for the Production of Calorimeter Subsystem in a Safe Environment

11.9 Safety

Figure 26 defines the integrated approach use for subsystem safety.

11.10 Reliability

The high reliability required on this program will be achieved by robust designs use of heritage hardware, including design margins, by the manufacturing processes and controls imposed at every level of fabrication, assembly, subcontracts and test. The design margin will ensure that the Calorimeter subsystem is capable of performing in the operation environment.

The predictive modeling approach takes place in two successive stages as shown in Figure 27. CAL international partners and subcontractors shall also maintain a reliability program that is planned, scheduled, integrated, and developed in conjunction with development at NRL.

The inherent reliability of the design is determined by analysis, part and material selection, part application, stress derating, and worst case analysis. The actual reliability is determined by the realities of part and assembly testing, production assembly, quality control, vendor surveillance, incoming inspection and maintenance.

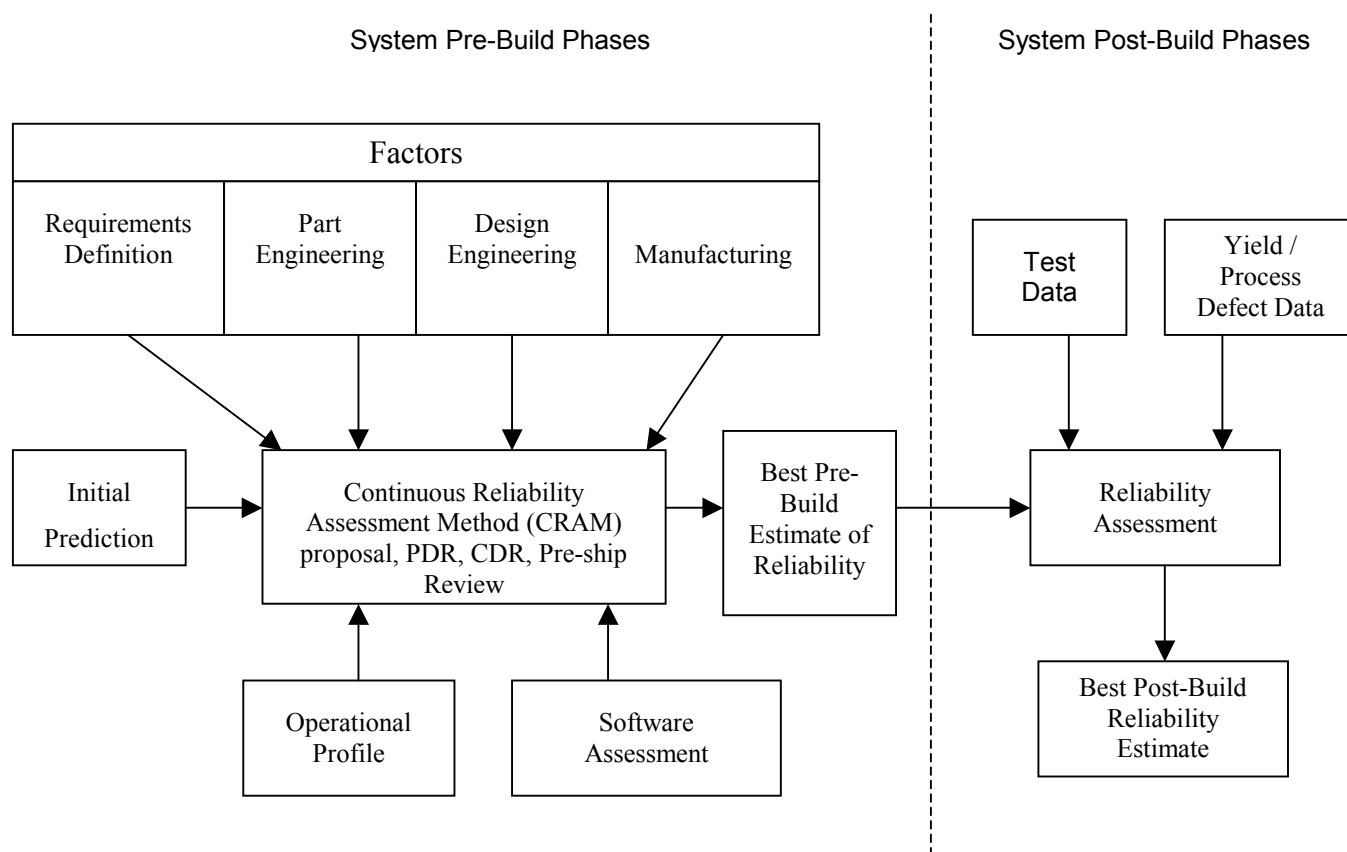


Figure 27. Prediction Using Component Reliability Assessment Method

12 VM AND EM DEVELOPMENT

The formulation phase of the CAL program leading up to the Preliminary Design Review is focused on demonstrating solutions to the key technical challenges in the CAL design. In the area of the PEM and CDEs, the objectives are

- demonstration of the PIN to CsI bonding solution,
- demonstration of the light yield from the CDEs mounted, as planned, in the PEM
- verification of the PEM mechanical design and integrity of the CDEs mounted in the PEM.

In the area of the electronics, the objectives are

- finding rad hard COTS ADC and DAC
- demonstrating analog ASIC performance

The PEM and CDE testing will be performed with the development of the VM2 verification model. This unit is a complete PEM mechanical structure. It will contain 12 active CsI Detector Elements and 84 CDE dummies for environmental testing. Light yield and integrity tests will be performed on the CDE before and after environmental testing.

The Engineering Model Calorimeter that will be built before the CAL Critical Design Review will be a complete prototype in form, fit, and function. Commercial grade parts will be substituted where necessary. The schedule calls for of functional, science performance and environmental testing.

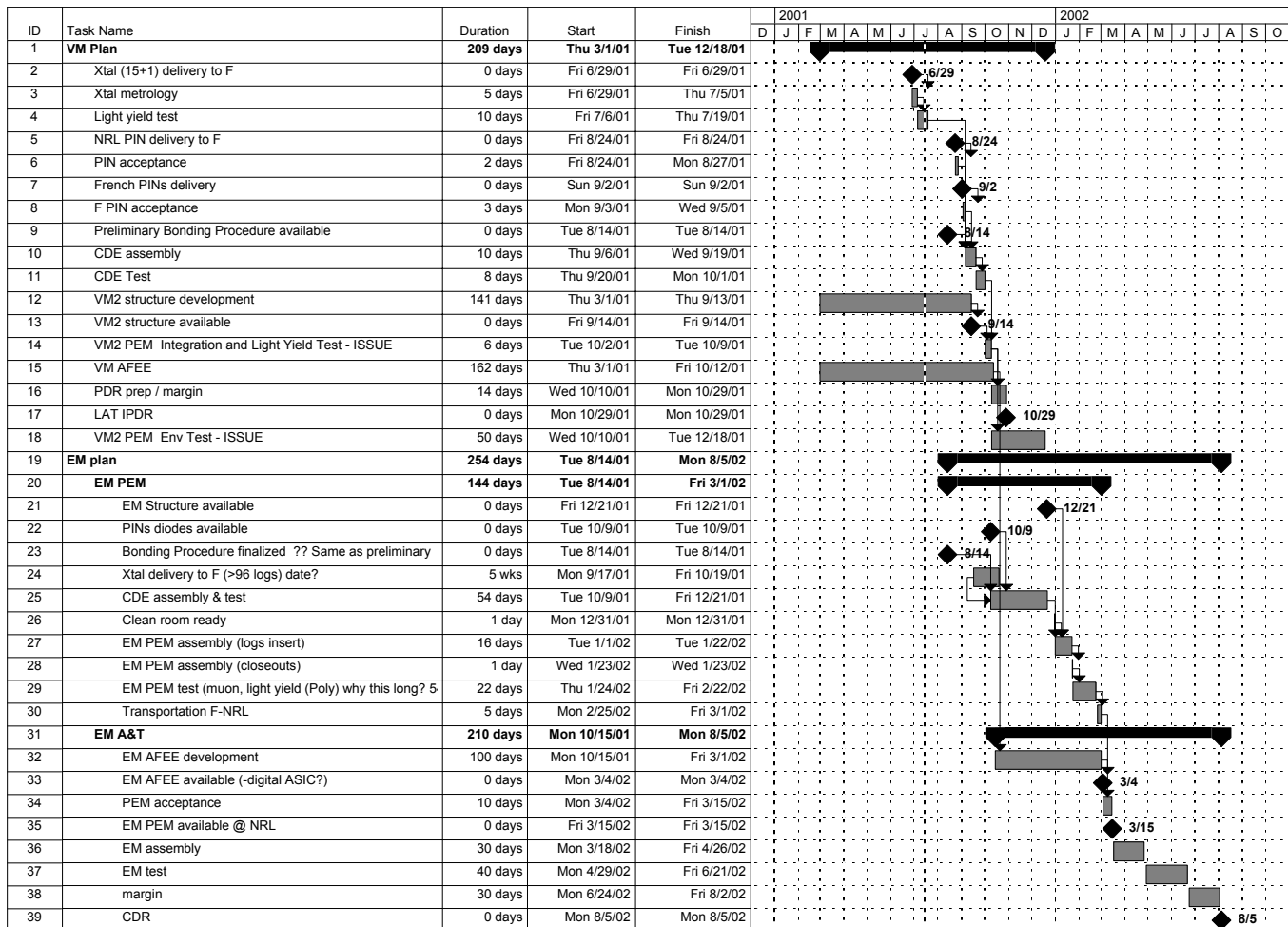


Figure 28. Verification and Engineering Models Development Schedule

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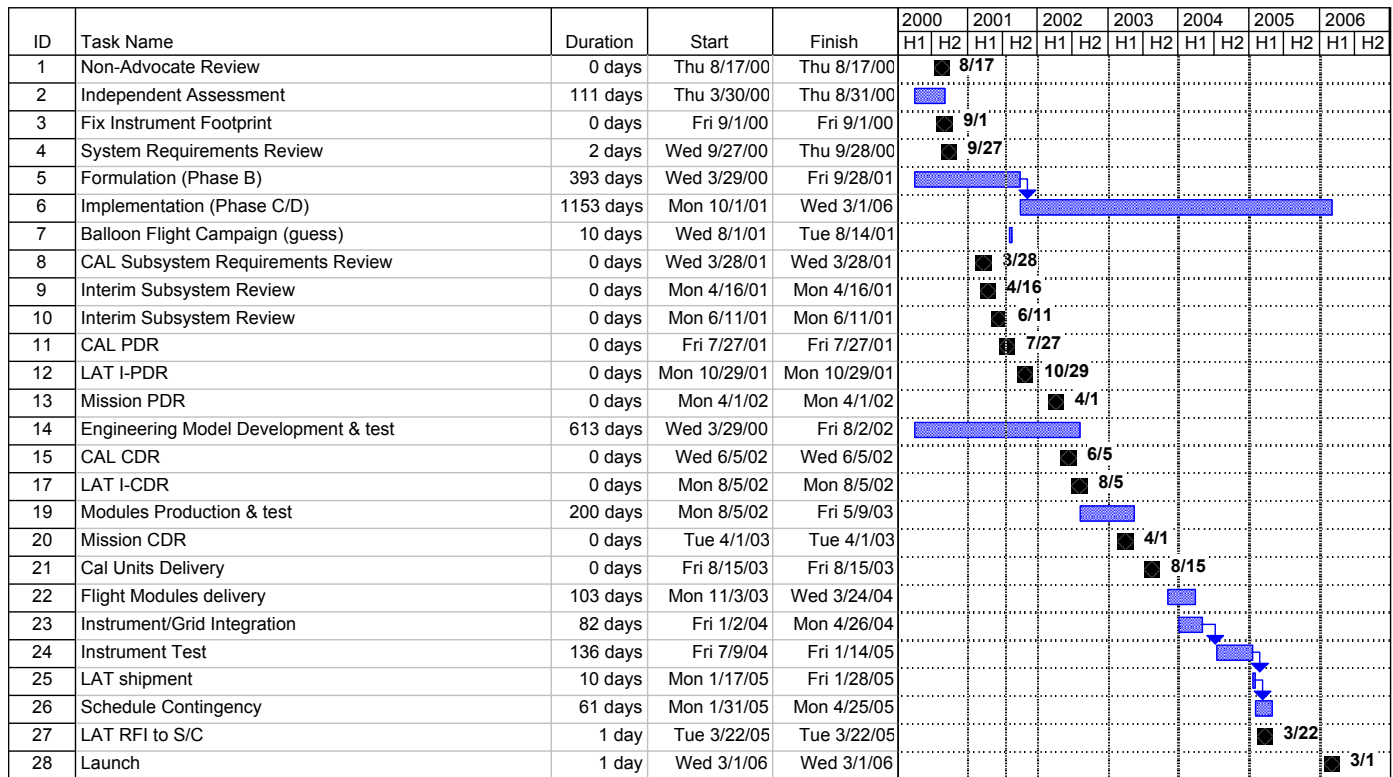


Figure 29. CAL and LAT Program Milestones

13 SCHEDULE

Figure 29 displays the top level milestones of the LAT and Calorimeter Schedule. Table 12 summarizes the schedule for delivery of completed CAL modules to LAT Integration and Test.

Table 12. CAL Module Delivery Schedule

Module	Module Delivery Date	LAT Schedule Integration Date
Flight Model A (Qual)	05/13/03	08/15/03
Flight Model B	06/03/03	08/15/03
Flight Model 1	07/29/03	11/03/03
Flight Model 2	08/19/03	11/03/03
Flight Model 3	08/27/03	01/02/04
Flight Model 4	09/10/03	01/02/04
Flight Model 5	09/24/03	01/15/04
Flight Model 6	10/08/03	01/15/04
Flight Model 7	10/15/03	01/29/04
Flight Model 8	10/29/03	01/29/04
Flight Model 9	11/12/03	02/12/04
Flight Model 10	11/26/03	02/12/04
Flight Model 11	12/10/03	02/26/04
Flight Model 12	12/24/03	02/26/04
Flight Model 13	01/07/04	03/10/04
Flight Model 14	01/21/04	03/10/04
Flight Model 15	02/04/04	03/24/04
Flight Model 16	02/18/04	03/24/04

14 APPENDIX

Preliminary parts list

Reports of modeling and simulation

Test Reports